STUDY OF RHEOLOGY OF GAS-TO-LIQUID (GTL) PRODUCTS, ALASKA NORTH SLOPE CRUDE OIL AND THEIR BLENDS FOR TRANSPORTATION THROUGH THE TRANS ALASKA PIPELINE SYSTEM (TAPS)

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A

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ABSTRACT

In order to bring remote natural gas to market, conversion of natural gas to a liquid form (Gas-to-liquids (GTL)) may be an alternative to utilize this gas. Alaskan North Slope might prove as one of the first sites in the USA to commercialize this technology because of the huge natural gas resources it holds. The Trans Alaska Pipeline System (TAPS) will be the means of transportation of this GTL to the market. Thus it becomes major task to evaluate the technical and economic feasibility of transporting GTL products through the TAPS.

One of the modes of transporting GTL products from ANS to Valdez is commingling them with Crude oil as a single phase before pumping through TAPS. This changes the properties of GTL as well as the Crude oil. Thus it becomes important to study the physical and chemical properties of not only the GTL but also its blends with the crude oil. Four blends of GTL/crude in the ratios of 1:1, 1:2, 1:3 and 1:4 were prepared for their rheological evaluation at different temperature conditions.

Results show that flow behavior of the pure and GTL blends are temperature sensitive. Viscosity and density of the blends decrease with increasing amount of GTL and increasing temperature. Optimum blend ratio is between 1:2 and 1:3 GTL/Crude oil blends.

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CHAPTER 1
INTRODUCTION

1.1 INTRODUCTION

The Alaskan North Slope (ANS) has a huge amount of natural gas reserves, which can be exploited in many different ways. It is seen as an excellent economic potential for the state of Alaska. The estimated ANS proven and recoverable reserves of natural gas in known oil and gas reservoirs is about 38 trillion standard cubic feet (TCF). Currently the Natural Gas in the Alaska North Slope is primarily used for pressure maintenance, miscible injection, running gas turbines in pump stations 1 to 4, power oil production facilities and for Enhanced Oil Recovery (EOR) projects. Most of the gas may remain unused upon depletion of North Slope recoverable oil and will thus be stranded unless a means of transportation is developed to make it marketable.

The various options being examined for operational and economic feasibility for the optimum use of ANS natural gas include: constructing a new Alaska Natural Gas Transportation System (ANGTS) to transport the gas to lower 48 states via Canada; constructing a shorter Liquefied Natural Gas (LNG) pipeline to Valdez from where the gas would be shipped to the markets; and converting the gas to gas-to-liquid products (GTL), blend it with the ANS crude oil and transport the resulting liquid through the existing Trans Alaska Pipeline System (TAPS). Previous studies proved that the best of these three options is the third option (that is, the GTL option). The GTL technology might also prove the best method for monetizing other stranded natural gas reserves worldwide.

With the dwindling production of oil from the ANS fields, the throughput of oil into the Trans Alaska Pipeline System (TAPS) is declining steadily and is expected to continue to decline in future. It is projected that by the year 2015, ANS crude oil production will decline to such a level (200,000 to 400,000 bbl/day) that there will be a critical need for pumping additional liquid through the pipeline in order to maintain economic operation of the TAPS (Khataniar et al, 2004). Production of GTL from ANS natural gas and transporting it through TAPS will increase the pipeline throughput and its economic life.

The TAPS was specifically designed for transporting ANS crude oil. Introduction of GTL products into the pipeline might lead to some operational problems. Anticipated problems include altered pumping power requirements, possibility of vapor formation, solids precipitation and deposition and gel formation. It is very essential to investigate these anticipated problems prior to commencing construction of GTL facilities at the ANS. As a result, a three-year research project, funded by the US Department of Energy (USDOE) is being carried out at the Petroleum Development Laboratory, University of Alaska Fairbanks to investigate these anticipated operational challenges.

Altered pumping power requirements depend on the pressure drop due to a particular fluid. Rheology of fluid can affect this pressure drop. Rheology is the study of flow and deformation of fluid. Every fluid shows typical rheological behavior. Thus understanding of rheology of GTL and its blends with crude oil also becomes important in the transportation of GTL products through the Trans Alaska Pipeline System.

Shell Oil Company, Bintelu, Malaysia provided non-ANS-originated GTL products that were used for earlier studies. BP Exploration Alaska Inc., a major lease holder at the ANS, provided ANS-originated GTL products for the study. Alyeska Pipeline service Company (APSC), the operator of TAPS, provided the ANS crude oil samples.

1.2 OBJECTIVES OF THIS STUDY

The objectives of this study are:

1) to evaluate rheology and density of GTL, ANS crude oil and their blends at different temperatures;
2) to determine and analyze the energy requirements for flowing the fluids through the TAPS;
3) and to determine the optimum GTL/Crude Oil blend ratio that can flow through the TAPS.

CHAPTER 2
LITERATURE REVIEW

2.1 GAS-TO-LIQUIDS (GTL)

GTL is a process that converts natural gas to liquid petroleum products - diesel, naphtha, and waxes - using Fischer-Tropsch technology. GTL products are free of toxic impurities; sulfur compounds, nitrogen compounds and aromatics, which make them clean burning fuels. Sulfur oxides (SOx) and Nitrogen oxides (NOx) are the dangerous compounds that are responsible for the ever-growing worldwide pollution, green house effect and global warming. Thus the highly pure GTL products will definitely have an an added advantage compared to presently used fuels since they will easily meet most of the Environmental Protection Agency norms.

What's important for a GTL Project? (Conoco GTL Brochure, 2002)

• Gas reserves of 4.0 – 4.5 TCF to sustain 500 MMCFD feed for 25 years - more reserves are better.

• Gas price around $0.50/MMBTU (depending on gas quality)

• Rich gas feed - the higher the BTU content, the better

• Integration opportunities with other industrial facilities - LNG, petrochemical, power plants, refineries, etc.

2.1.1 Fischer-Tropsch:

The Fischer-Tropsch (F-T) process is a method of converting natural gas to liquids. The discovery of F-T chemistry in Germany dates back to the 1920s and its development has been for strategic rather than economic reasons, as in Germany during World War II and in South Africa during the apartheid era. In the F-T reaction, synthesis gas (CO and H_2) reacts over a catalyst to produce a mixture of straight-chain hydrocarbons that can be treated to produce transport fuels. The technology has been in existence for many years but has only found limited commercial application.

2.1.2 Gas-To-Liquid (GTL) Technology overview

This process creates a synthesis gas through steam reforming and partial oxidation of methane, and then polymerizes this gas to produce various denser hydrocarbon mixtures, that can be refined into numerous products. GTL production is a chemical process that produces permanent and stable liquid from natural gas. GTL products are stable middle distillate fractions with higher cetane rating (cetane number =75) than the conventional diesel fuels and contain no polynuclear aromatics, sulfur or nitrogen compounds. The GTL products are obtained by essentially a three-step conversion.

1) Synthesis Gas (Syngas) Production ($CO+H_2$) mixed in 2:1 ratio over a 200°C Nickel and Cobalt catalyst.
2) Synthetic Crude (Syncrude) production or Heavy paraffin synthesis (Reforming and Polymerization, CH_N).
3) Heavy Paraffin conversion or refining (Hydrocracking to improve the quality of naphtha or diesel base products).

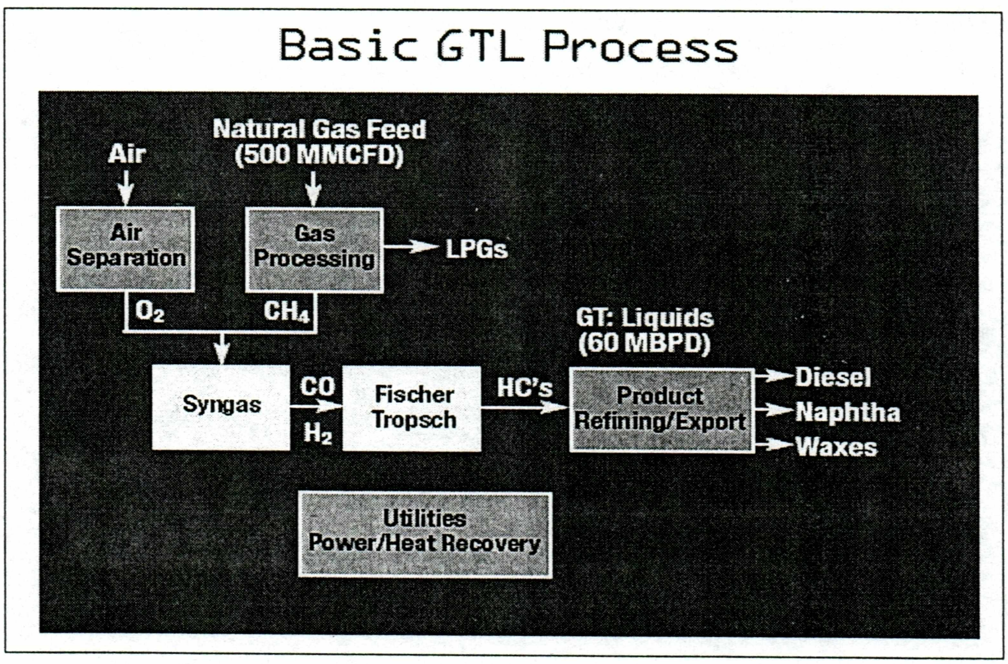

Figure 2.1 Basic GTL process for production of GTL from natural gas. (Courtesy: Conoco)

Synthesis gas ($CO + H_2$) is produced in the first step from natural gas by steam reforming, partial oxidation or auto thermal reforming of natural gas. In second step the syngas produced is chemically converted to higher hydrocarbon liquids. Various GTL conversion process are available with the F-T synthesis processes (Liu, 1999). The Fischer Tropsch synthesis is a polymerization reaction that uses CH_x monomers derived from syngas to form high molecular weight hydrocarbons. It is conducted in F-T reactors, which could be a fixed bed, fluidized bed or slurry bed reactors. The fixed bed reactor is used primarily to produce diesel while the fluidized bed reactor is to produce gasoline. The third step involves upgrading F-T products and is used to improve liquid fuel selectivity and quality of GTL products. The upgrading is achieved by oligomerization of the C_3 to C_6 olefins and hydrocracking of waxes. Fig 2.1 above shows the schematic of basic GTL process.

The synthesis gas generation process is a major component of the capital expense of any GTL facility (Aucoin, 2002). The existence of the TAPS makes the possibility of transporting GTL less capital intensive and hence more feasible. It is possible that the flow of GTL will maintain the economic viability of the TAPS. The current estimates show that TAPS is uneconomical when the daily production is below 300,000bbls.

The schematic commercialization of stranded natural gas resources using GTL technology has received much attention from both the government and private industry. As new GTL technologies have improved and matured, energy companies continue to invest significant money to move improved GTL technologies from small pilot facilities to commercial developments. British Petroleum Exploration Alaska (BPXA) has already started the production of GTL from pilot GTL facility in Nikiski, Alaska and also started the production to demonstrate a new synthesis gas generation technology and assess challenges of GTL production in a cold climate. Experiences from this facility may be applied to a possible commercial GTL facility on the ANS.

GTL products are less viscous than crude oil. The viscosity of North Slope oil has been increasing with the increase in production of oil. The TAPS was originally designed for less viscous fluids. Thus due to increasing viscosity of the present crude oil might have adverse effects on the life of TAPS. The blending of the light GTL products with crude oil would help in retaining the API of the fluid that the TAPS was originally designed for. Also presently the daily transfer of fluid through TAPS is less than the capacity of TAPS. This increases the tariff on the pipeline. Transporting GTL through TAPS would meet the capacity of TAPS and would decrease the tariff. Considering all the points mentioned above the GTL option for exploiting the ANS natural gas might prove to the best option. In order to present effective analysis of the GTL transportation through TAPS, the issues that are to be addressed are like cold restart problems, solid deposition, corrosion and wax precipitation problems, hydraulics of GTL and its blends with crude oil, phase behavior etc. based on the optimal transport mode.

2.2 MODES OF FLOW

The two modes of flow considered for GTL transportation through TAPS are:

1) *Batch mode*: - The transport of GTL and crude oil in slugs or batches results in creation of an interface zone between both fluids. This interface zone is made up of air pockets and a mixture of both fluids. The magnitude of the interface zone is a function of the fluid velocity, density differences, viscosity, pipe diameter, pipe length, time and composition (Baum et al, 1998). A complex two-phase flow is created by this mode.

2) *Commingled mode*: - In this mode of transportation, the crude oil and GTL are blended before being sent through the pipeline as a single liquid phase mixture.

Both modes were studied. The pressure drop and energy balance equations were determine for both batch and commingled flow modes of transporting GTL through the TAPS. The solutions to these equations were presented for determining pressure gradient and optimum slug length for batch operations. The Bernoulli equation of pressure for the flow of fluids in pipes was used to derive flow equations applicable to specified operating conditions or constraints of the Trans Alaska Pipeline System (TAPS), (Akwukwaegbu, 2001). *The results of the Akwukwaegbu study indicates that the pressure gradient obtained from the batch flow calculations are higher than those obtained from that of commingled flow.* The reason being that for batch flow, the pressure gradient is the ratio of the total pressure drop across the slug to the length of the slug, whereas for commingled flow, it is the ratio of the total pressure drop to the length of the pipe segment. In pressure drop calculations different flow patterns that might occur in either batch or commingled flow should be taken into account.

In commingled mode of flow calculations, the GTL and crude oil samples were premixed to represent a single phase fluid system. Since GTL and Crude oil are both hydrocarbons they should have a similar fluid properties and a homogenous mixture can be expected. This was initially practically backed by the results of the tests carried out at Petroleum Engineering Department at UAF (Ramakrishnan, 2000). Phase behavior results presented by Sharma (2003) show that at TAPS temperature and pressure conditions the mixture of GTL and crude oil is single homogenous phase. Thus in this study, the GTL/crude oil blends will be treated as a single liquid phase.

2.3 OPTIMAL TRANSPORT ISSUES

The following factors should be addressed for an optimal transportation mode of GTL through TAPS:

1) Storage and handling facilities should be provided at both the terminals for any transport mode.
2) Additional facilities in case of batch mode for maintaining the purity of fluids.
3) Pressure losses within the system should be determined.
4) The phase behavior of the GTL products should be studied.
5) Effect of solids precipitation (wax, asphaltenes etc) within the pipeline should be examined.
6) Ability of the facility to handle GTL transportation, which has higher API from the original design specification of transporting crude between 24 and 32°API.
7) Determination of GTL gelling temperatures and a complete rheology of the products with their implication on TAPS operations.
8) The interaction of GTL with chemicals such as corrosion inhibitors, drag reducers, which are currently used for crude oil, transport through TAPS.

9) Temperature effects on GTL and GTL crude oil blends.
10) Cost benefit analysis of transporting GTL through TAPS as opposed to building a new pipeline.

Extensive work on many of the factors mentioned above is being carried out in Petroleum Development Laboratory at UAF. The efforts of this work will concentrate on the temperature effects on rheology of GTL/ Crude Oil blends.

2.4 THE COEFFICIENT OF VISCOSITY

Viscosity is associated with the ability of a fluid to flow freely. The idea of viscosity being proportional to time to flow has become accepted practice in the petroleum industry. Thus the motorist purchases oil with a viscosity labeled SAE 30. This means that 60 ml of this oil at a specified temperature takes 30 seconds to run out of a 1.76-cm hole in the bottom of a cup. This experiment is convenient and reproducible for very viscous liquids such as oil, but the time to flow is not a measure of viscosity.

A more fundamental approach to viscosity shows that it is the property of a fluid that relates applied stress to the resulting strain rate. A simple and widely used example of fluid sheared between two plates, as in figure 2.2 is used to explain this concept. This geometry is such that the shear stress τ_{xy} must be constant throughout the fluid.

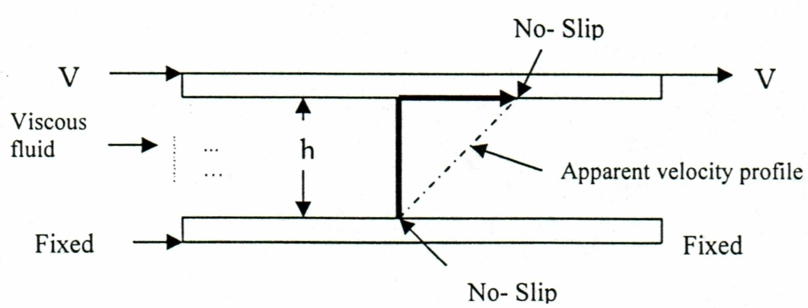

Figure 2.2 A fluid sheared between two plates.

The motion is in the x-direction and varies with y, u = u (y) only. Thus there is only a single finite strain rate in this flow:

$$\in_{xy} = \frac{1}{2}\left(\frac{\partial u}{\partial y} + \frac{\partial v}{\partial x}\right) = \frac{1}{2}\frac{\partial u}{\partial y} = \frac{1}{2}\frac{du}{dy} \quad \text{-- (2.1)}$$

For all common fluids, the applied shear is unique function of the strain rate:

$$\tau_{xy} = f(\in_{xy}) \quad \text{-- (2.2)}$$

For a given motion V of the upper plate τ_{xy} is constant, hence in these fluids $\in_{xy}$ is constant. This makes du/dy constant and thus the resulting velocity profile is linear across the plate, as shown in figure 2.2. This is true regardless of the actual form of the functional relationship in Equation 2.2. If the no-slip condition holds, the velocity profile varies from zero at the lower wall to V at the upper wall. Repeated experiments with various values of τ_{xy} will establish the functional relationship (equation 2.2). For simple fluids such as water, oil, or gases, the relationship is linear or *Newtonian*:

$$\tau_{xy} \sim \in_{xy} \quad \text{or} \quad \tau_{xy} = \mu\frac{V}{h} = 2\mu \in_{xy} = \mu\frac{du}{dy} \quad \text{---------------------------- (2.3)}$$

The quantity μ, called the coefficient of viscosity of a Newtonian fluid is commonly known as absolute viscosity of fluid. Equation 2.3 shows that the dimensions of μ is stress-time. The coefficient μ is a thermodynamic property and varies with temperature and pressure.

If the functional relationship in equation 2.2 is non-linear, the fluid is said to be *non-Newtonian*. Figure 2.3a shows the examples of non-Newtonian behavior of fluids. Curves for true fluids, which cannot resist shear, must pass through the origin on a plot of shear stress vs. shear rate. Other substances, called yielding fluids, show a finite stress at zero strain rates and are really part fluid and part solid.

The curve labeled *pseudoplastic* in figure 2.3a is said to be shear thinning since its slope(local viscosity) decreases with increasing stress. If the thinning effect is very strong, the fluid may be termed *plastic*, as shown. The opposite case of a shear thickening fluid is usually called a *dilatant* fluid, as shown.

Also illustrated in figure 2.3a is a material with a finite yield stress, followed by a linear curve at finite shear rate. This idealized material, part solid and part fluid, is called a *Bingham plastic*. Yielding substances need not be linear but may show either dilatant or pseudoplastic behavior as shown in figure 2.3c.

Still another complication of some non-Newtonian fluids is that their behavior may be time-dependent. If the strain rate is held constant, the shear stress may vary, and vice versa. If the shear stress decreases, the material is called thixotropic, while the opposite effect is termed rheopectic. These curves are also shown in figure 2.3b.

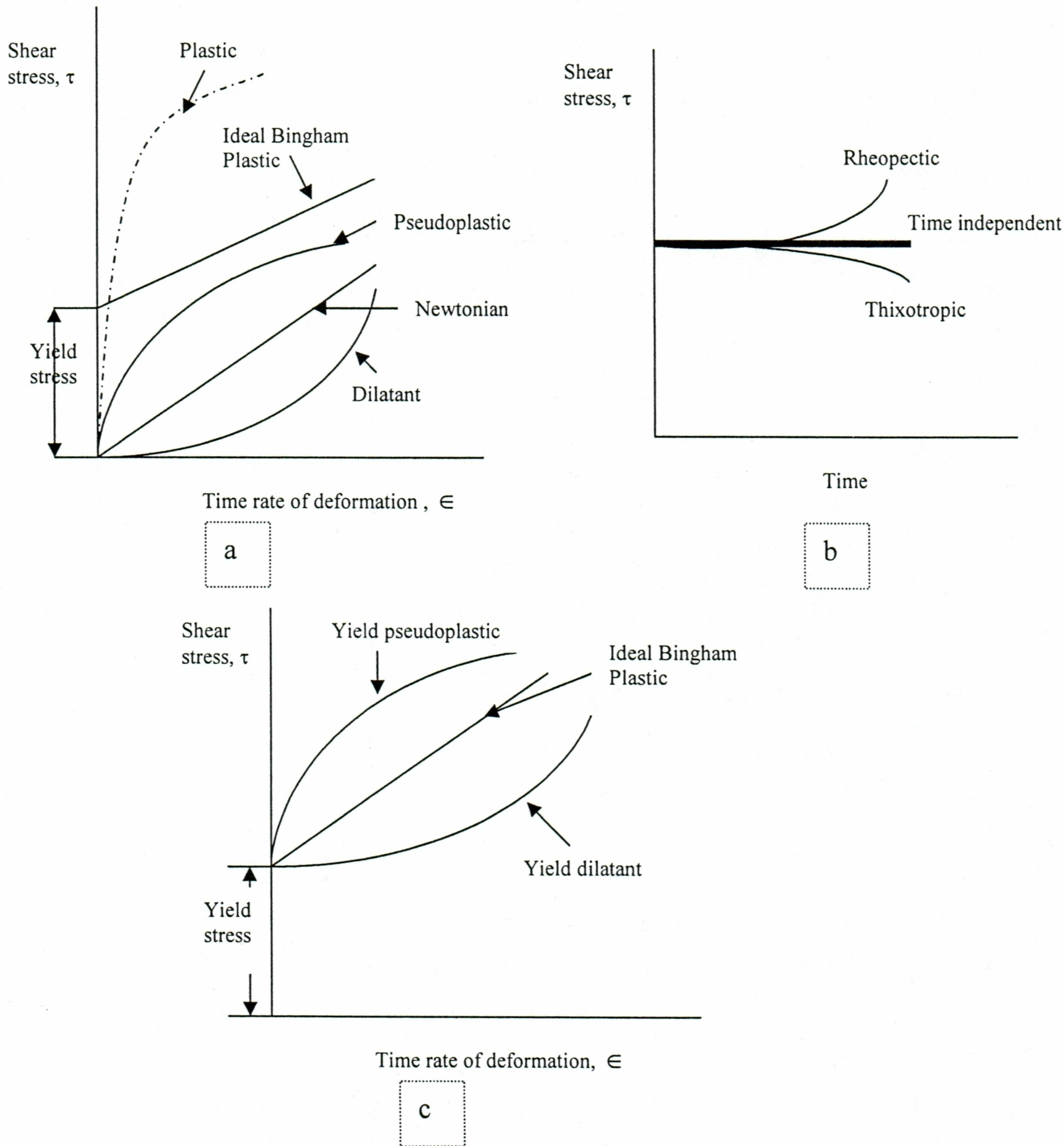

Figure 2.3 Viscous behavior of various materials

2.5 RHEOLOGY

Rheology = Greek verb "to flow"

Rheology means the study of flow and deformation. In principle, rheology includes everything dealing with flow behavior: aeronautics, hydraulics, fluid dynamics, and even solid mechanics. However in practice rheology has usually been restricted to the study of the fundamental relations, called constitutive relations, between force (or shear stress) and deformation (or shear strain) in materials, primarily fluids.

When a fluid is flowing, a force exists in the fluid that opposes the flow. This force is known as shear stress, which can also be seen as the frictional force between the two adjacent layers of fluid. And the relative velocity with which an individual layer moves with the neighboring layers is shear rate. The shear stress is a function of pressure and the shear rate is a function of geometry and average velocity of the fluid. The relationship between shear stress and shear rate defines the flow behavior of the fluid. The different behaviors explained above and sketched in figure 2.3 define the similar rheological behavior when we consider the deformation or strain is due to shear stress. The plot of shear stress-shear rate relationship is called *rheogram,* which shows rheology of fluid and is also used to determine the viscosity of the fluid.

2.5.1 Classification of Newtonian and non-Newtonian fluids

A) Newtonian Fluids

In 1987 Newton published in his "Principia" the simplest statement which delineates the viscous behavior of nearly all common fluids: "The resistance which arises from the lack of lubricity in the parts of a fluid – other things being equal -- is proportional to the velocity by which the parts of fluid are being separated from each other. Such fluids, water and air being prominent examples, are called Newtonian in his honor. Thus his law of linear viscosity can be written in equation as:

Shear stress = [(constant) x (shear rate)] or $\tau = \mu \dot{\gamma}$ -------------------------------- (2.4)

This constant μ is called absolute or true viscosity of the fluid that is defined to be shear stress divided by shear rate. The viscosity of a Newtonian fluid is constant.

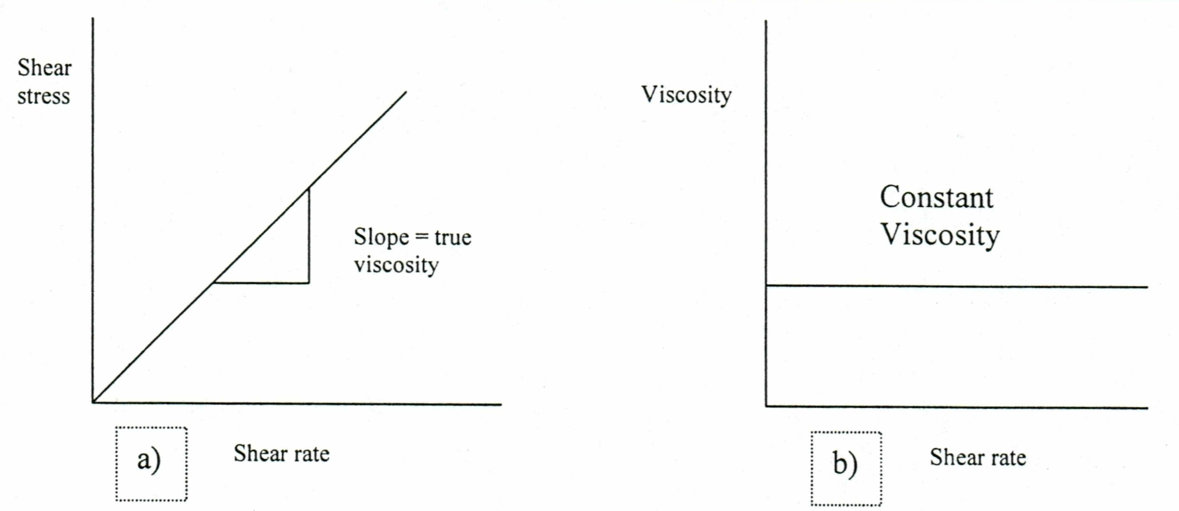

Figure 2.4 Newtonian fluids

B) Non-Newtonian Fluids

The shear stress-stress rate relationship for Newtonian fluid is described by the simple mathematical equation 2.4. Thus to determine exactly the rheogram for a Newtonian fluid it is only necessary to know the shear stress at a single shear rate. That point is then plotted on rectangular co-ordinate paper, and a straight line is drawn through that point and the origin.

To determine exactly the rheogram for a non-Newtonian fluid, it is necessary to use an infinitely variable speed viscometer. There is no one mathematical equation that will precisely describe the rheology of non-Newtonian fluids. Various rheological models have been proposed that approximate to some degree the true shear stress-shear rate relationship. A good rheological model should have the following properties:

1. It should closely approximate the true shear stress-shear rate relationship
2. It should be based on measurements that can be made routinely in the field, and
3. It should be sufficiently simple that inferences and calculations based on it can be carried out in the field.

a) Power-law model

Power-law model is given by the following equation

$$\tau = k(\dot{\gamma})^n \quad \text{-- (2.5)}$$

where,

n is power-law index factor

k is consistency index factor

n and k are called the parameters of power-law model. The parameter n shows the degree of deviation of fluid from Newtonian fluid. Based on the value of n, fluids can be classified as follows:

$n = 1$ --------- Newtonian examples: air, water, high viscosity fuels

$n < 1$ --------- Pseudoplastic examples: grease, printer's ink, soap

$n > 1$ --------- Dilatant examples: clay, starch in water, peanut butter

The shear stress shear rate behavior of power law fluid is shown in figure 2.5a.

Taking log of both sides of equation 2.5 gives equation 2.6

$$\log\tau = n\log\dot{\gamma} + \log k \quad \text{-- (2.6)}$$

A plot of $\log\tau$ vs. $\log\dot{\gamma}$ can be used to get the values of n and k (see figure 2.5b)

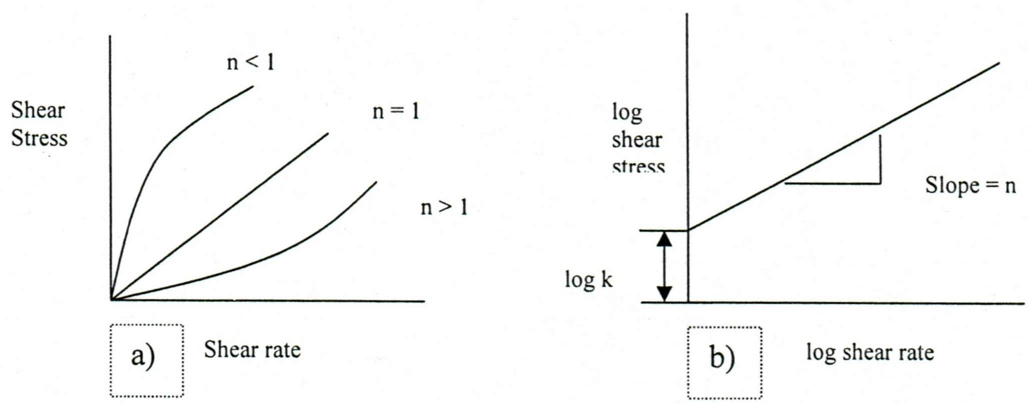

Figure 2.5 Power-law fluids

b) Bingham Plastic model

The equation for Bingham plastic model is:

$$\tau = \mu_p(\dot{\gamma}) + YP \quad \text{------} \quad (2.7)$$

where,

μ_p or PV is called plastic viscosity

YP is the yield point

Plastic viscosity is usually described as that part of resistance to flow caused by mechanical friction. Primarily, it is affected by

1. Solids concentration
2. Size and shape of solids, and
3. Viscosity of the fluid phase.

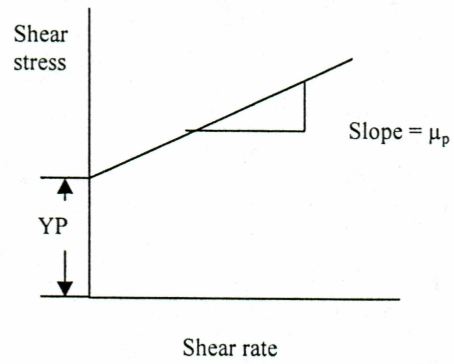

Figure 2.6 Bingham plastic fluids

Thus an increase in plastic viscosity generally means an increase in the percent by volume of solids, a reduction in size of the solid particles, a change in the shape of the particles, or a combination of these.

Yield point is that part of the resistance to flow caused by the attractive forces between particles.

CHAPTER 3
EXPERIMENTAL METHODOLOGY

3.1 SAMPLE PREPARATION:

Laporte light GTL was used for the initial experimental investigation in this study. This GTL was distilled in three sample cuts as suggested by Timmcke (2002) at temperatures 254, 302 and 344 degree Celcius so that a wide range for GTL that may be transported through TAPS is obtained for the study. Herzog HDA 627 Automatic Distillation Apparatus was used for the distillation. The detailed operating instructions for distilling the Laporte Light GTL had been earlier presented by Ramakrishanan (2000) and Timmcke (2002). Figure 3.1 shows Herzog HDA 627 Atmospheric Distillation Apparatus used for the distillation. In January 2004 GTL field samples were received from BP Alaska GTL pilot plant. The BP sample is referred as BPGTL or GTL and the sample cuts are denoted as GTL254, GTL302 and GTL344.

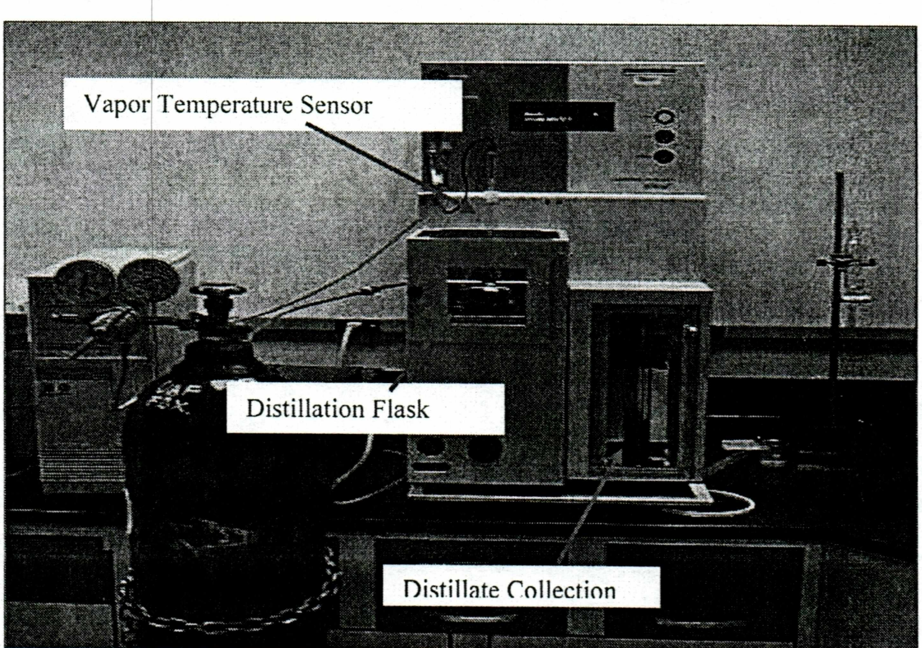

Figure 3.1 Herzog HDA 627 Atmospheric Distillation Apparatus

3.1.1 Crude Oil Sampling, Reconditioning and Aliquoting

Alyeska Pipeline Service Company (APSC) supplied all the crude oil samples used in this study. The samples were taken at pipeline conditions and preserved in constant pressure welker cylinders. Before aliquoting the samples, it is necessary to recondition the samples back to the original pipeline conditions. This is done to ensure that the pipeline compositions of the samples are retained. Detailed procedure for crude oil Reconditioning and Aliquoting is as outlined by Ramakrishnan, 2000. Figure 3.2 shows the Welker cylinder.

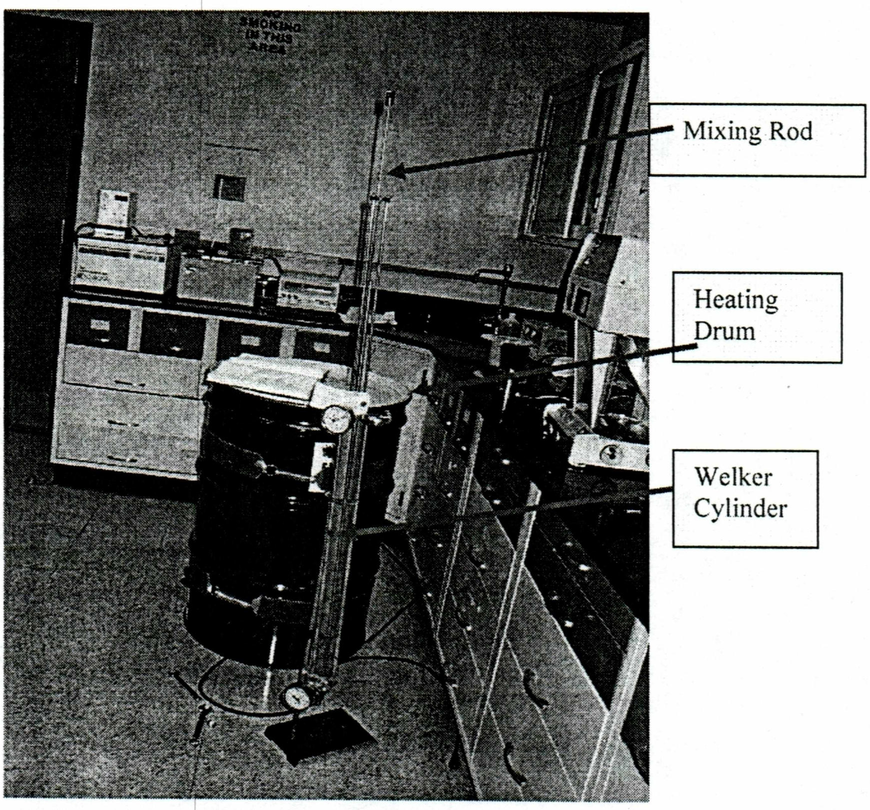

Figure 3.2 Welker Cylinder and 55 gal Drum with Industrial Belt Heaters

3.2 DENSITY MEASUREMENTS

A thorough knowledge of densities is useful for determining pressure drop in a pipeline system. The sample blends used in this study were blended gravimetrically, and for accurate blending, densities of GTL samples and crude oil were required. Density measurements were carried out in the GTL research laboratory for GTL, crude oil and their blends. The Anton-Paar digital densitometer DMA 45 (Figure 3.3) was used for the measurement of densities of the samples. The operating procedures and calibration of the Anton-Paar digital densitometer has been adapted from Ramakrishnan (2000). The density meter setup was modified slightly to enable more accurate control of bath temperature near room temperature. A refrigerated circulating bath was connected to the circulating constant-temperature bath described by Ramakrishnan (2000). A refrigeration bath, circulating bath and the digital densitometer are placed next to each other, see figure. 3.3. The Refrigeration bath is connected to the circulating bath in case lower temperatures are required or a sudden drop in temperature is to be achieved. The temperature selector in the circulating bath is selected to the desired temperature in the analyzer of the densitometer. The densitometer is now ready to be calibrated at the temperature on which the densities are desired. Calibration and operating procedures are discussed in detail in Ramakrishnan (2000).

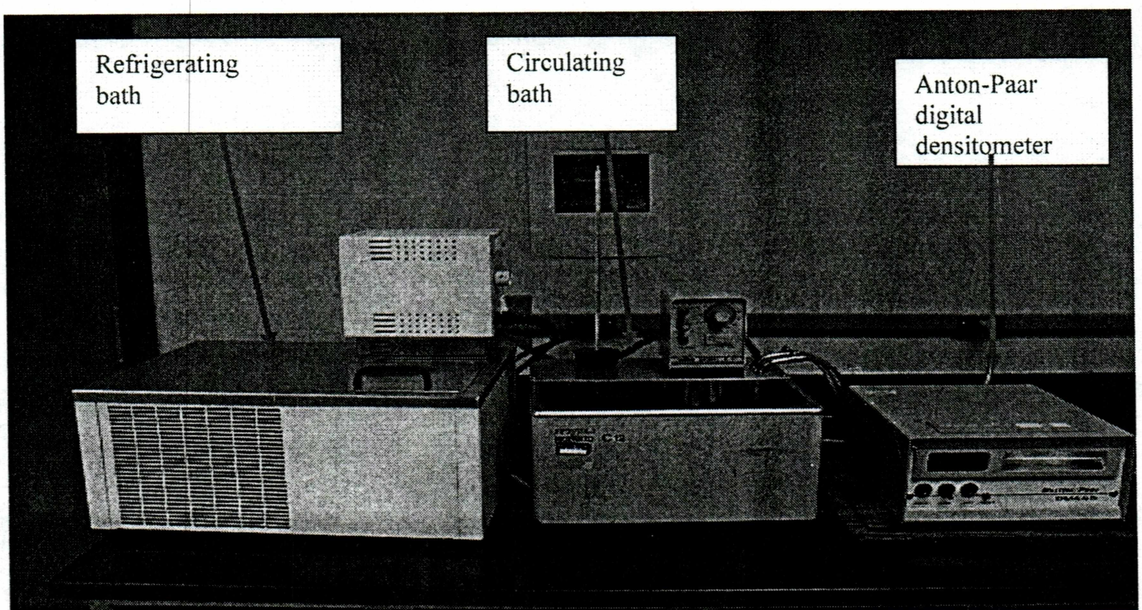

Figure 3.3 Anton-Paar DMA 45 Digital Densitometer

3.3 BLENDING OF SAMPLES

GTL and crude oil sample blends are prepared gravimetrically in the ratios of 1:1, 1:2, 1:3 and 1:4.

3.3.1 Blending Procedure

1. Determine the required quantity of sample needed to perform the desired test.
2. Based on the density of the sample components and the volume of the blend required, determine the mass of each component necessary to provide the required volume of the component in the blend, at the given mass ratio.

   Using

   $$V = \frac{\alpha M}{\rho_G} + \frac{(1-\alpha)M}{\rho_C} \qquad \text{--- (3.1)}$$

   Therefore

   $$M = \frac{\rho_G \rho_C V}{\rho_C \alpha + (1-\alpha)\rho_G} \qquad \text{--- (3.2)}$$

   Where

   α is the mass fraction of GTL in the blend

   M is the total mass of the blend that will give the required volume.

   With M calculated, the blend can be made using either Mass balance or Pipette

   Using Mass balance:

   Mass of GTL = αM --- (3.3)

   Mass of Crude = (1-α)M --- (3.4)

   Using Pipette:

   $$\text{Volume of GTL} = \frac{\alpha M}{\rho_G}. \qquad \text{-- (3.5)}$$

   $$\text{Volume of Crude} = \frac{(1-\alpha)M}{\rho_C} \qquad \text{-- (3.6)}$$

3.3.2 Example Calculation

To blend **100ml** of 1:3 GTL302/Crude oil sample, the following steps are taken:

i. Determine the density of each of the components

Density of GTL302 at 21°C = 0.7296 gm/cc

Density of crude oil at 21°C = 0.8641 gm/cc

ii. Determine the mass of the blend that will give 100ml

M= (0.7296*0.8641*100)/ ((0.8641*0.25) + (0.7296*0.75))

Mass of GTL302= 0.25x82.6 = 20.65 gm

Mass of Crude = 0.75x82.6 = 61.95 gm

iii. Determine the volume of each component (if using pipette)

Volume of GTL302 = 0.25*82.6/0.7296 = **28.303 ml**

Volume of Crude Oil = 0.75*82.6/.8641 = **71.693 ml**

3.4 VISCOSITY MEASUREMENTS

The calibration and operation of the Brookfield LV DVII+ Cone/Plate Viscometer are adapted from Ramakrishnan (2000). The Julabo refrigerated bath circulates heat transfer fluid through the Cone/Plate viscometer and the two gel strength viscometers simultaneously and, thus, the temperature may not be independently controlled. To increase the heat transfer efficiency of the system, a custom fit polystyrene insulating jacket was made to fit over the sample chamber of the Cone/Plate viscometer.

This insulating jacket should be installed during the viscosity test at extreme temperatures. Figure 3.4 shows the temperature controlled sample chamber with its precisely machined plate and the CPE-40 cone spindle used in this work. The output data from the viscometer are tabulated in table 3.1.

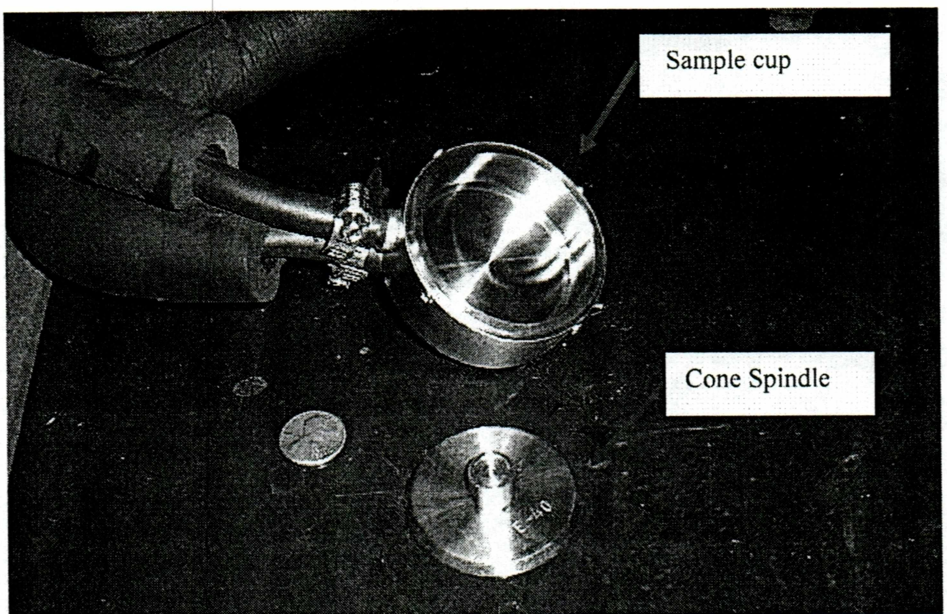

Figure 3.4 LV DVII+ Cone/Plate Sample Chamber.

Table 3.1 Output data from Brookfield viscometer for Crude oil at 21 deg C.

WinGather V1.1 data Copyright 1995, Brookfield Engineering Laboratories

Date: 11/06/03 Model: LV

Time: 13:38 Spindle: CP40

File: CRUDE Sample:UNNAMED DATA

Speed	Torque	Viscosity	Shear Stress	Shear Rate	Temperature	Time
RPM	%	mPas	N/m2	1/sec	øC	sec
0.5	1.5	9.2	0.3	3.8	21.0	228
1.0	3.6	11.0	0.8	7.5	21.1	66
2.5	10.7	13.1	2.5	18.8	21.0	66
5.0	18.8	11.5	4.3	37.5	21.1	48
10.0	40.2	12.3	9.2	75.0	21.1	49
15.0	59.4	12.1	13.7	113.0	21.1	54
20.0	79.9	12.2	18.4	150.0	21.1	42
25.0	100.0	12.3	23.1	188.0	21.1	49

After getting this data shear stress shear rate are plotted on the Cartesian graph and the rheology is studied. Viscosity is obtained from the slope of this data after multiplying the slope by 100. Experiments were carried out to measure viscosity of GTL cuts, BPGTL, crude oil and their blends at different temperatures. The results and observations are discussed in chapter 5.

CHAPTER 4
ENERGY AND PRESSURE GRADIENT EQUATIONS

4.1 PIPELINE SPECIFICATIONS

The Trans Alaska Pipeline System (TAPS) is 800.32 miles long with inner diameter of 46.98 inches. The average pipeline thickness is 0.512 inches. It starts at Prudhoe Bay and ends at Valdez terminal with a total line fill of 9.06 MMbarrels. Its maximum design pressure and maximum operating pressure is 1180 psi. The original design of the pipeline has 12 pump stations with 4 pumps each. Pump station 5 is a relief station with no pumping capacity. Pump stations 2, 6, 8, 10 and 12 are currently shut down. The Control system of the pipeline provides instantaneous monitoring and control of all significant aspects of operation and pipeline leak detection. The locations of the various pump stations with their elevations are shown in table 4.1. Figure 4.1 is the map of Alaska showing the Trans Alaska Pipeline System and the pump stations. Trans Alaska pipeline maximum daily throughput is 2.136 million barrels, with 11 pump stations operating. Rates exceed 1440,000 bbl/day with drag reduction agent (DRA) injection.

Table 4.1 Locations and Elevation of Pump Stations (TAPS FACTS, 2004)

Pump Station	Location	Distance	Elevation
		Miles	Feet
1	Prudhoe Bay	0	39
2	Happy Valley	57.76	602
3	Happy Valley	104.27	1383
4	Galbraith Lake	144.05	2763
5	Prospect Creek	274.74	1066
6	Five Mile	354.94	881
7	Fairbanks	414.12	905
8	Eielson AFB	489.22	1029
9	Big Delta	548.69	1509
10	Gulkana	585.77	2392
12	Gulkana	735.04	1821
Terminal	Valdez	800.27	142

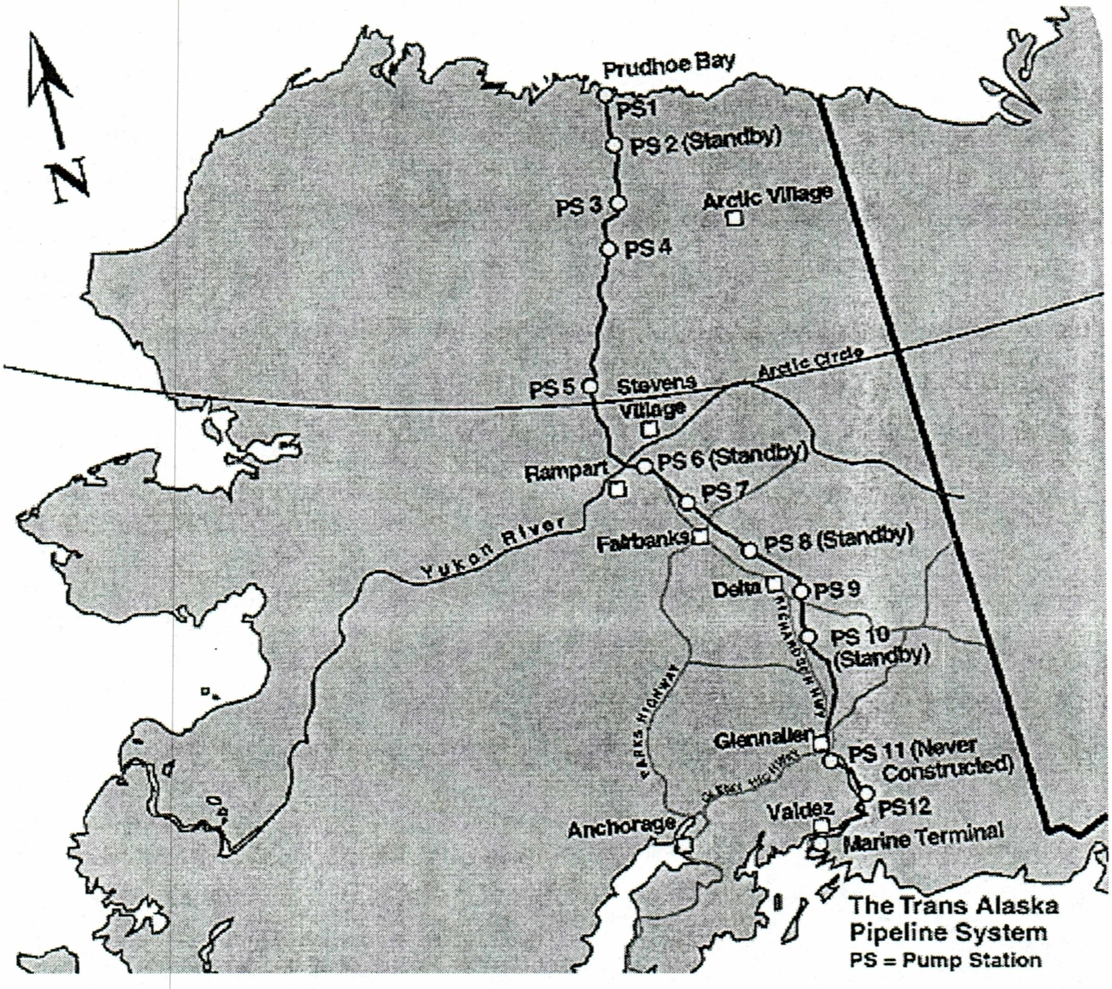

Figure 4.1 Map of Alaska showing the Trans Alaska Pipeline and the pump stations.

4.2 TRAVEL TIME AND TEMPERATURES OF CRUDE OIL

The crude oil travels at an average velocity of 3.7 miles per hour and the total time it takes to travel from pump station one to Valdez is 9 days. The travel time for each pipe section is shown in table 4.2. (www.alyeska-pipe.com)

The inlet and exit temperature of the crude oil at working pump stations are shown in table 4.3 (Chrisman, 2004)

Table 4.2 Travel Miles and Line Fill Between Stations (Pipeline Facts, 2004)

Travel time at 1.02 million bbl./day and miles and line fill between stations				
From		**Hours**	**Miles**	**Line fill (bbl.)**
PS	1-2	15.71	57.76	653,862
PS	2-3	12.65	46.51	526,508
PS	3-4	10.82	39.78	450,322
PS	4-5	35.56	130.77	1,480,358
PS	5-6	21.81	80.18	907,663
PS	6-7	16.09	59.18	669,937
PS	7-8	20.42	75.10	850,156
PS	8-9	16.17	59.46	673,106
PS	9-10	10.09	37.09	419,871
PS	10-11	27.24	100.16	1,133,843
PS	11-12	13.36	49.11	555,941
PS	12- Valdez	17.74	65.22	738,311
		217.65	**800.32**	**9,059,879**

Table 4.3 Crude oil Temperatures at Various Pump Stations

Pump Station	Inlet Temperature (deg C)	Exit Temperature (deg C)
1		45.9
3	26.3	28.6
4	26.2	26.9
5	Relief Station	
7	14.3	16.0
9	16.9	18.5
Valdez	14.9	

The above temperatures are for a flow rate of 1.02 MMbpd for the month of February, 2004. The TAPS operating pressure is 1500 psi.

4.3 GENERAL ENERGY EQUATIONS

The solution of conservation of energy between two points in a system gives the general energy equation. Many fluid flow equations are based on this general energy equation. The energy balance states that the summation of i) energy of a fluid entering a control volume, ii) shaft work done on or by the fluid, iii) heat energy added to or taken from the fluid, iv) change of energy with time in control volume must equal the energy leaving the control volume.

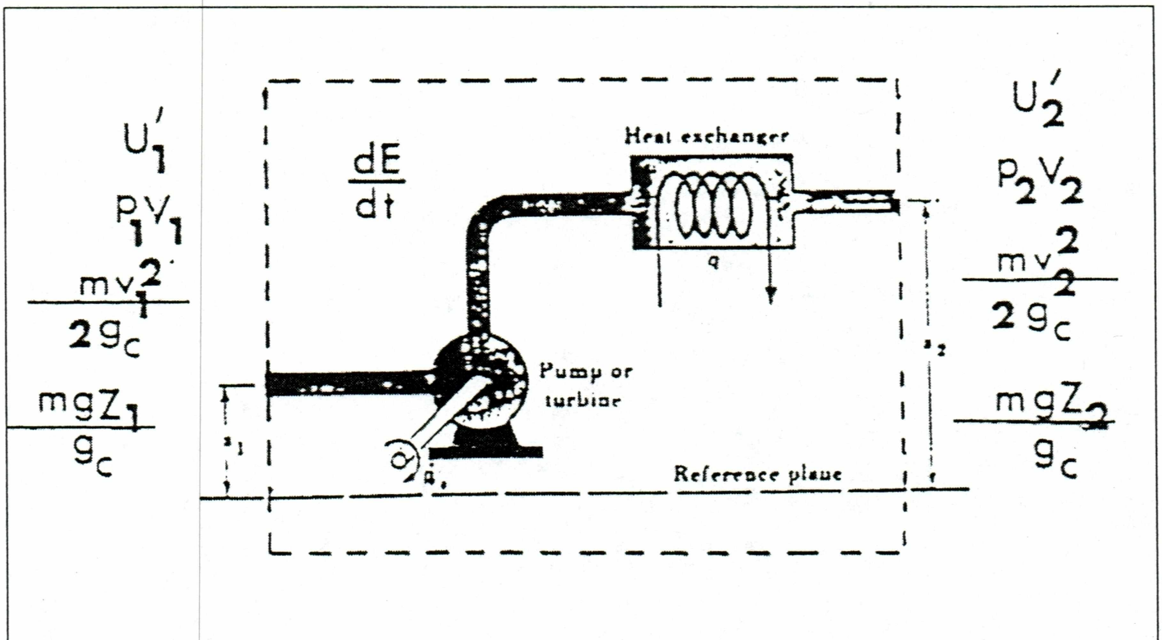

Figure 4.2 Flow System control Volume (Brill et. al, 1994)

The energy balance for a steady state system is written as

$$U_1'+P_1V_1+\frac{mv_1^2}{2g_c}+\frac{mgz_1}{g_c}+q'+W_s'=U_2'+P_2V_2+\frac{mv_2^2}{2g_c}+\frac{mgz_2}{g_c} \quad \text{----- (4.1)}$$

Equation 4.1 is divided by m to obtain the energy per unit mass balance. The differential form for energy per unit mass is given in equation 4.2

$$dU + d\left(\frac{p}{\rho}\right) + \frac{vdv}{g_c} + \frac{g}{g_c}dz + dq + dW_s = 0 \quad \text{------} (4.2)$$

We know

$$dU = TdS + \frac{dp}{\rho} - d\left(\frac{p}{\rho}\right) \quad \text{------} (4.3)$$

Equation 4.4 is obtained by substituting equation 4.3 in equation 4.2

$$TdS + \frac{dp}{\rho} - d\left(\frac{p}{\rho}\right) + d\left(\frac{p}{\rho}\right) + \frac{vdv}{g_c} + \frac{g}{g_c}dz + dq + dW_s \quad \text{------} (4.4)$$

Using Clausis inequality relationship and assuming no work is done on or by the fluid, Equation 4.4 becomes

$$\frac{dp}{\rho} + \frac{vdv}{g_c} + \frac{g}{g_c}dz + dL_w = 0 \quad \text{------} (4.5)$$

where dLw = losses due to irreversibilities, such as friction.

The pipe through which fluid is flowing is not always horizontal. Consider the pipe inclined at some angle θ to the horizontal, as shown in figure 4.2.

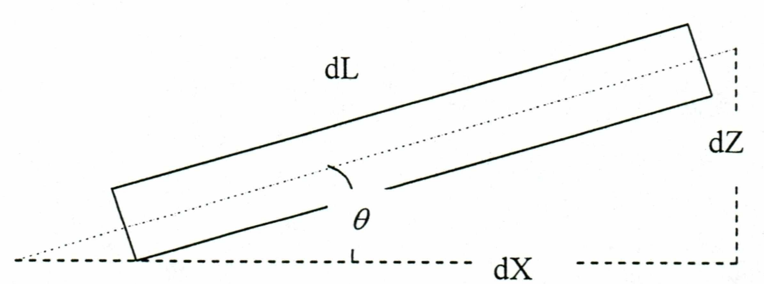

Figure 4.3 Inclined pipe geometry.

We now have dz = dL $\sin\theta$, and multiply the equation by $\frac{\rho}{dL}$ to get

$$\frac{dp}{dL}+\frac{\rho v dv}{g_c dL}+\frac{g}{g_c}\rho\sin\theta+\rho\frac{dL_w}{dL}=0 \quad \text{-- (4.6)}$$

This equation can be solved for pressure gradient, and if we consider a pressure drop as being positive in the direction of flow

$$\frac{dp}{dL}=\frac{g}{g_c}\rho\sin\theta+\frac{\rho v dv}{g_c dL}+\left(\frac{dp}{dL}\right)_f \quad \text{-- (4.7a)}$$

where,

$$\left(\frac{dp}{dL}\right)_f \equiv \rho\frac{dL_w}{dL} \text{ is the pressure gradient due friction losses ----------------- (4.7b)}$$

4.4 FRICTION FACTOR

Friction factor plays important role in evaluation of pressure drop in pipe. In horizontal pipe flow the energy losses or pressure drop is caused by change in kinetic energy and friction losses only. Friction factor is defined as the ratio of wall shear stress (τ_w) to kinetic energy per unit volume ($\rho v^2/2g_c$). Friction factor is dimensionless.

$$f'=\frac{\tau_w}{\rho v^2/2g_c}=\frac{2\tau_w g_c}{\rho v^2} \quad \text{-- (4.8)}$$

The well known Fanning friction factor equation is given as

$$\left(\frac{dp}{dL}\right)_f=\frac{2f'\rho v^2}{g_c d} \quad \text{-- (4.10)}$$

In terms of Darcy-Weishbach or Moody friction factor, $f_m = 4f'$, and

$$\left(\frac{dp}{dL}\right)_f=\frac{f_m\rho v^2}{2g_c d} \quad \text{-- (4.11)}$$

Based on Reynolds number the flow regime is classified as laminar or turbulent. And for both these regimes friction factors are documented. For laminar flow friction factor in terms of Reynolds number is given in equation 4.12 and 4.13.

$$f_m = \frac{64\mu}{\rho v d} = \frac{64}{N_{\mathrm{Re}}} \quad \text{------------------------------------} \quad (4.12)$$

The equivalent expression for the Fanning friction factor is

$$f = \frac{16}{N_{\mathrm{Re}}} \quad \text{--} \quad (4.13)$$

Since velocity profile and pressure gradient are sensitive to pipe wall characteristics three cases of pipe wall can be considered to define friction factor in turbulent flow; a) smooth wall pipe, b) partially rough wall and c) fully rough wall pipe

For *smooth wall pipes* Drew, Koo and McAdams'(1932) equation is most commonly used since it is explicit in f and also covers a range of Reynolds numbers 3000 < N_{Re} < 3 x 10^6. This equation is given as:

$$f = 0.0056 + 0.5 N_{\mathrm{Re}}^{-0.32} \quad \text{--} \quad (4.14)$$

In practice the inside of a pipe is not normally smooth. In turbulent flow, the roughness can have a definite effect on the friction factor and thus the pressure gradient. Dimensional analysis suggests that effect of roughness is not due to its absolute dimensions, but rather to its dimensions relative to the inside diameter of the pipe, ε/d. Nikuradse's correlation for fully rough wall pipe is still the best one available which is given as:

$$\frac{1}{\sqrt{f}} = 1.74 - 2\log_{10}\left(\frac{2\varepsilon}{d}\right) \quad \text{--} \quad (4.15)$$

Colebrook and White proposed the following equation in 1939. In 1944, Moody published his well-known chart for determining the friction factor for turbulent flow in pipes as a function of Reynolds number and relative pipe wall roughness (Gregory et. al., 1985).

$$\frac{1}{\sqrt{f}} = 1.74 - 2\log_{10}\left(\frac{2\varepsilon}{d} + \frac{18.7}{N_{\mathrm{Re}}\sqrt{f}}\right) \quad \text{----- (4.16)}$$

A trial and error method is used to calculate this friction factor.

Several explicit equations for calculating the friction factor of rough pipe were developed in later years. Some of them are listed below.

Jain (1976)

$$\frac{1}{\sqrt{f}} = 1.14 - 2\log_{10}\left(\frac{\varepsilon}{d} + \frac{21.25}{N_{\mathrm{Re}}^{\;0.9}}\right) \quad \text{----- (4.17)}$$

Chen (1979)

$$\frac{1}{\sqrt{f}} = -4\log\left[\frac{\varepsilon / D}{3.7065} - \frac{5.0452}{N_{\mathrm{Re}}}\log\left\langle\frac{(\varepsilon / D)^{1.1098}}{2.8257} + \left(\frac{7.149}{N_{\mathrm{Re}}}\right)^{0.8981}\right\rangle\right] \quad \text{----- (4.18)}$$

Zigrang and Sylvester (1982)

$$\frac{1}{\sqrt{f}} = -4\log\left[\frac{\varepsilon / D}{3.7} - \frac{5.02}{N_{\mathrm{Re}}}\log\left\langle\frac{\varepsilon / D}{3.7} + \frac{13}{N_{\mathrm{Re}}}\right\rangle\right] \quad \text{----- (4.19)}$$

The pressure gradient equation, which is applicable to any fluid at any pipe inclination angle, is given as

$$\frac{dp}{dL} = \frac{g}{g_c}\rho\sin\theta + \frac{f\rho v^2}{2g_c d} + \frac{\rho v dv}{g_c dL} \quad \text{----- (4.20)}$$

The total pressure gradient is composed of three components:

$$\frac{dp}{dL} = \left(\frac{dp}{dL}\right)_{el} + \left(\frac{dp}{dL}\right)_{f} + \left(\frac{dp}{dL}\right)_{acc} \quad \text{----- (4.21)}$$

where

i) $\left(\frac{dp}{dL}\right)_{el} = \frac{g}{g_c}\rho\sin\theta$ is the elevation change component. It if also referred to as the hydrostatic component, as it is the only component that would apply at conditions of no flow. Thus this component is zero for horizontal flow. It applies for compressible, steady state or transient flow in both vertical and inclined flow. For downward flow the sine of the angle is negative and the hydrostatic pressure increases in the direction of flow.

ii) $\left(\frac{dp}{dL}\right)_{f} = \frac{f\rho v^2}{2g_c d}$ is the friction loss component. This component applies for any type of flow at any pipe angle. It always causes a drop of pressure in the direction of flow. In laminar flow the friction losses are linearly proportional to the fluid velocity. In turbulent flow the friction losses are proportional to v^n where $1.7 \leq n \leq 2$, where n is turbulent factor which depends on fluid properties.

iii) $\left(\frac{dp}{dL}\right)_{acc} = \frac{\rho v dv}{g_c dL}$ is the acceleration component. This component applies for all transient flow conditions, but is zero for constant area, incompressible flow. For any flow condition in which a velocity change occurs, such as compressible flow, a pressure drop will occur in the direction of the velocity increase.

4.4.1 Steps followed for calculation of frictional pressure losses

A. Newtonian model (Procedure adopted by APSC)

1. If not given, assume flow rate q in SBPH.
2. Flow rate in BPD is calculated as:

$$q_{BPD} = \frac{q_{SBPH} \times 24}{1 - TE_{coeff} \times (FT - 60)} \qquad (4.22)$$

3. Flow rate in gallons per minute (GPM) is calculated as:

$$q_{GPM} = \frac{q_{BPD} \times 42}{24 \times 60} \qquad (4.23)$$

4. Velocity v is estimated using following equation

$$v = \frac{924 \times q_{GPM}}{720 \times \pi \times d^2} \quad \text{-- (4.24)}$$

5. Calculated Reynolds number as:

$$N_{Re} = \frac{sp.gr. \times 62.3709 \times v \times d}{0.008064 \times \mu} \quad \text{-- (4.25)}$$

6. Estimate Darcy friction factor as:

$$f = 8\left[\left(\frac{8}{N_{Re}}\right)^{12} + (A+B)^{-1.5}\right]^{1/12} \quad \text{-- (4.26)}$$

where A and B are given as

$$A = \left[2.457 \times \ln\left(\left[\frac{7}{N_{Re}}\right]^{0.9} + .27 \times \frac{\varepsilon}{d}\right)^{-1}\right]^{16} \quad \text{-- (4.27)}$$

$$B = \left(\frac{37{,}530}{N_{Re}}\right)^{16} \quad \text{-- (4.28)}$$

7. Head loss is calculated using following equation:

$$H_f = \frac{f \times L \times v^2}{2 \times D \times g_c} \quad \text{-- (4.29)}$$

8. Frictional pressure loss is calculated as:

$$\left(\frac{dp}{dL}\right)_f = \frac{H_f}{2.31} \times sp.gr. \quad \text{-- (4.30)}$$

B. Power Law Model.

1. If not given assume the flow rate q in BPD.
2. Flow rate in gallons per minute (GPM) is calculated as:

$$q_{GPM} = \frac{q_{BPD} \times 42}{24 \times 60} \quad \text{-- (4.31)}$$

3. Calculate mean velocity, v, using the equation

$$v = \frac{924 \times q_{GPM}}{720 \times \pi \times d^2} \quad \text{or} \quad v = \frac{q}{2.448d^d} \quad \text{-- (4.32)}$$

4. Flow behavior parameters n and k are obtained from the experimental shear stress shear rate data (See tables 5.6 through 5.11). Here K is in equivalent centipoises. [K=510k]

5. Calculate Reynolds number using the equation

$$N_{Re} = \frac{89100\rho v^{2-n}}{K}\left(\frac{0.416d}{3+1/n}\right)^n \quad \text{-- (4.33)}$$

NRe < 2100 – laminar flow; NRe > 2100 – Turbulent flow

6. Estimate laminar flow frictional pressure loss using equation:

$$\left(\frac{dp}{dL}\right)_f = \frac{Kv^n\left(\frac{3+1/n}{0.0416}\right)^n}{144{,}000d^{1+n}} \quad \text{-- (4.34)}$$

7. Estimate turbulent flow frictional pressure loss using equation:

$$\left(\frac{dp}{dL}\right)_f = \frac{fL\rho v^2}{25.8d} \quad \text{--- (4.35)}$$

where

f is friction factor which is obtained from figure 4.4.

C. Bingham Plastic Model

1. Assume the flow rate q.

2. Calculate mean velocity, v, using the equation

$$v = \frac{q}{2.448d^d} \quad \text{--- (4.32)}$$

3. Plastic viscosity (μ_p) and yield point (τ_y) are obtained from the experimental shear stress shear rate data (See tables 5.7 through 5.10).

4. Calculate Reynolds number using the equation:

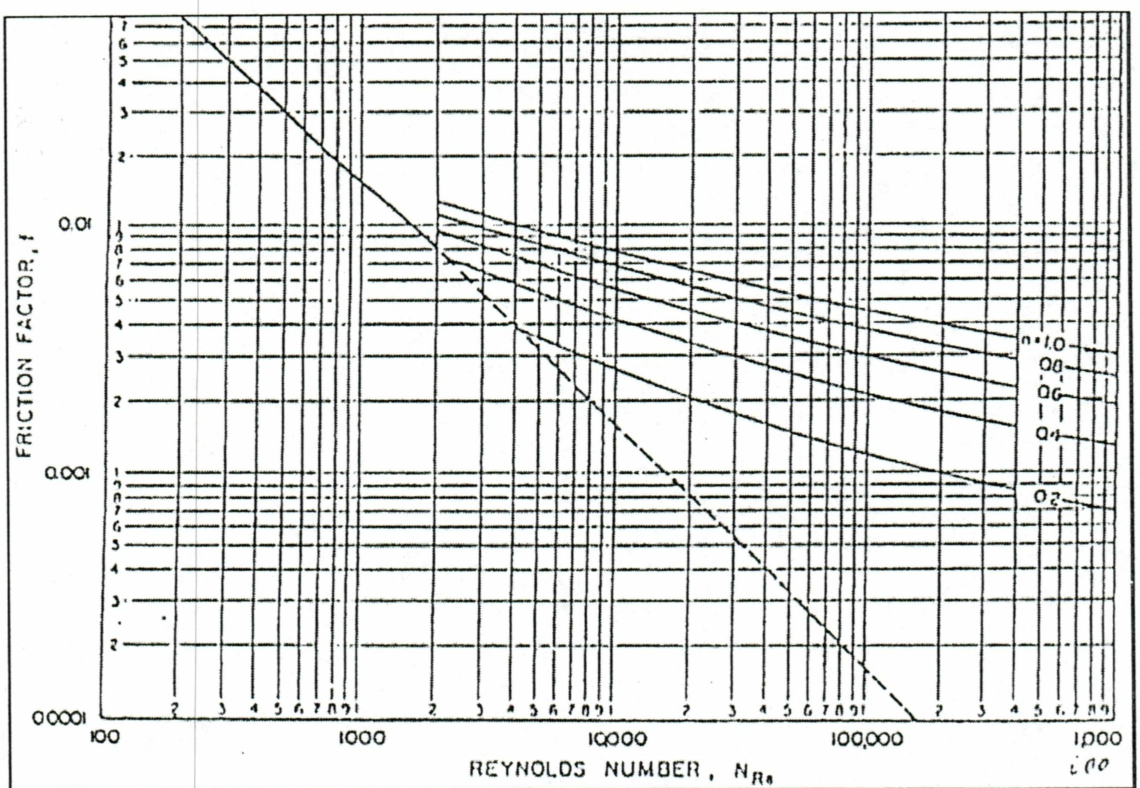

Figure 4.4 Friction factors for power-law model. (Brill et. al, 1994)

$$N_{Re} = \frac{37{,}100 \rho \tau_y d^2}{\mu_p^2} \quad \text{-------------------- (4.36)}$$

NRe < 2100 – laminar flow; NRe > 2100 – Turbulent flow

5. Estimate laminar flow frictional pressure loss using equation:

$$\left(\frac{dp}{dL}\right)_f = \frac{\mu_p v}{1500 d^2} + \frac{\tau_y}{225 d} \quad \text{-------------------- (4.37)}$$

6. Estimate turbulent flow frictional pressure loss using equation:

$$\left(\frac{dp}{dL}\right)_f = \frac{\rho^{.75} v^{1.75} \mu_p^{.25}}{1800 d^{1.25}} \quad \text{Or} \quad \left(\frac{dp}{dL}\right)_f = \frac{f \rho v^2}{25.8 d} \quad \text{-------------------- (4.38)}$$

where

f is friction factor which is obtained from figure 4.4.

4.5 EVALUATION of TOTAL PRESSURE DROP in TAPS

As discussed earlier in commingled flow of GTL and crude oil through TAPS the mixture is treated as single liquid phase. In order to find out total pressure drop in TAPS while transporting GTL and crude oil in commingled mode following assumptions are made:

i) Fluid flow is in steady state and fully developed.
ii) Flow is incompressible.
iii) There is no separation into constituent fluids.
iv) Isothermal fluid flow between two consecutive pumpstations
v) Fluid velocity is constant throughout.

Thus the total pressure drop now is due to friction, elevation change and other minor losses like through fittings etc. Equation 4.19 becomes

$$\Delta P = \left[\left(\frac{dp}{dL}\right)_f \times L\right] + \Delta P_{el} + \Delta P_{\min or} \quad \text{-- (4.39)}$$

where,

$\left(\frac{dp}{dL}\right)_f$ is calculated using equations stated above based on fluid behavior.

$$\Delta P_{el} = \frac{H_{el}}{2.31} \times sp.gr. \quad \text{-- (4.40)}$$

where H_{el} is the head due to elevation or elevation change in feet.

$\Delta P_{\min or}$ is assumed as shown in table 5.12.

4.6 POWER AND EFFICIENCY

The work performed by a pump is a function of the total head and the weight of the liquid pumped in a given time period. The pump capacity in gpm and the liquid specific gravity are normally used in the formulas rather than the actual weight of the liquid pumped.

Pump input or brake horsepower (BHP) is the actual horsepower delivered to the pump shaft. Pump output or hydraulic horsepower (HHP) is the liquid horsepower delivered by the pump. These two terms are defined by the following formulas.

$$HHP = \frac{Q \times H \times Sp.gr.}{3960} \quad \text{--} \ (4.41)$$

$$BHP = \frac{Q \times H \times Sp.gr.}{3960 \times Pumpefficiency} \quad \text{--} \ (4.42)$$

The constant 3960 is obtained by dividing the number or foot pounds for one horsepower (33,000) by the weight of one gallon of water (8.33 pounds.)

We know,

$$\Delta P = \frac{H \times Sp.gr.}{2.31} \quad \text{--} \ (4.43)$$

Thus in terms of pressure above hydraulic horsepower equation become

$$HHP = \frac{Q \times \Delta P}{1714} \quad \text{--} \ (4.44)$$

The brake horsepower or input to a pump is greater than the hydraulic horsepower or output due to the mechanical and hydraulic losses incurred in the pump. Therefore the pump efficiency is the ratio of these two values.

$$Pumpefficiency = \frac{HHP}{BHP} = \frac{Q \times H \times Sp.gr.}{3960 \times BHP} = \frac{Q \times \Delta P}{1714 \times BHP} \quad \text{-------------------} \ (4.45)$$

CHAPTER 5

RESULTS AND DISCUSSION

This chapter focuses on the results obtained from the experimental work. Shear stress and shear rate data are obtained from the cone plate viscometer. The data are used to determine viscosities and flow behavior parameters (n & k) of GTL, crude oil and their blends. These parameters and the regression coefficient (R^2) are used to classify the behavior of all the fluids discussed earlier. The value of R^2 closest to one indicates best fit. Density values obtained from the densitometer, viscosity values and the flow behavior parameters values are used to calculate the pressure gradients along TAPS. The energy requirement, based on hydraulic horsepower is estimated.

5.1 DENSITY MEASUREMENTS

The density of the GTL cuts, BPGTL, TAPS crude oil and their blends were determined in the laboratory using the Anton-Paar digital densitometer at atmospheric pressure. Two different crude oil samples were used to blend with the GTL cuts and BPGTL. This work concentrates more on study of BPGTL compared to the GTL cuts because BPGTL might be the representative sample of the GTL that would be produced from the ANS natural gas. A wide experimental range of temperature (0 deg C to 50 deg C) was selected for BPGTL and its blends with crude oil. The results obtained from the density measurements are shown in table 5.1 through table 5.4.

Table 5.1 : Density of GTL344, crude oil and their blends

Temperature		GTL344:Crude oil gravimetric blends Density (gm/cc)					
deg C	deg F	GTL344	1:1	1:2	1:3	1:4	Crude oil
21	69.8	0.7323	0.7962	0.8194	0.8275	0.8383	0.8641
15	59	0.7375	0.804	0.829	0.836	0.846	0.868
10	50	0.7412	0.8106	0.8371	0.8437	0.8527	0.8717
5	41	0.745	0.816	0.844	0.8492	0.858	0.8758
0	32	0.7494	0.8221	0.85	0.856	0.8635	0.879

Table 5.2 Density of GTL302, crude oil and their blends

Temperature		GTL302:Crude oil gravimetric blends Density (gm/cc)					
deg C	deg F	GTL302	1:1	1:2	1:3	1:4	Crude oil
21	69.8	0.7296	0.7919	0.8135	0.8266	0.8343	0.8641
15	59	0.736	0.8	0.8228	0.834	0.84	0.868
10	50	0.7401	0.8058	0.8273	0.8411	0.8452	0.8717
5	41	0.7438	0.8115	0.833	0.846	0.851	0.8758
0	32	0.7475	0.8162	0.8383	0.8515	0.858	0.879

Table 5.3 Density of GTL254, crude oil and their blends

Temperature		GTL254:Crude oil gravimetric blends Density (gm/cc)					
deg C	deg F	GTL254	1:1	1:2	1:3	1:4	Crude oil
21	69.8	0.7212	0.7889	0.8108	0.8251	0.83	0.8641
15	59	0.7239	0.796	0.82	0.831	0.8374	0.868
10	50	0.7258	0.8018	0.8258	0.8361	0.843	0.8717
5	41	0.729	0.8068	0.8296	0.84	0.8479	0.8758
0	32	0.7321	0.8104	0.8368	0.8436	0.8513	0.879

Table 5.4 Density of BPGTL, crude oil and their blends

Temperature		BPGTL/Crude oil gravimetric blends Density (gm/cc)					
deg C	deg F	GTL	1:1	1:2	1:3	1:4	Crude oil
0	32	0.7655	0.8354	0.8453	0.8488	0.8584	0.8753
5	41	0.7619	0.832	0.8416	0.8452	0.8547	0.8716
10	50	0.7582	0.8285	0.8378	0.8416	0.8511	0.8678
15	59	0.7545	0.825	0.8343	0.838	0.8474	0.8639
20	68	0.751	0.8215	0.8307	0.8344	0.8439	0.8603
22	71.6	0.7495	0.8201	0.8292	0.8329	0.8425	0.8587
25	77	0.7473	0.8183	0.8272	0.831	0.8406	0.8568
30	86	0.7439	0.8149	0.8239	0.8274	0.8372	0.856
35	95	0.7421	0.8133	0.8222	0.8257	0.8356	0.8544
40	104	0.7371	0.8085	0.8173	0.8208	0.8306	0.8492
45	113	0.7332	0.8048	0.8137	0.8168	0.8269	0.8455
50	122	0.7319	0.804	0.8127	0.816	0.8261	0.8445

The specific gravities of all the above fluids with respect to temperature are plotted in figures 5.1 through 5.4.

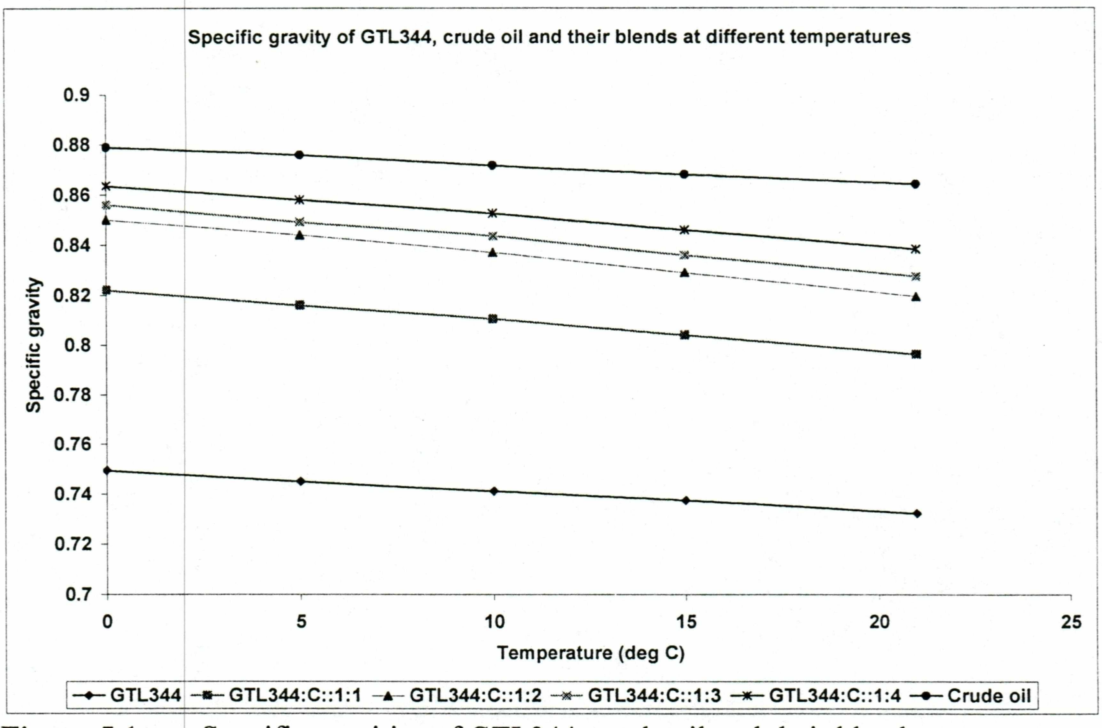

Figure 5.1 Specific gravities of GTL344, crude oil and their blends.

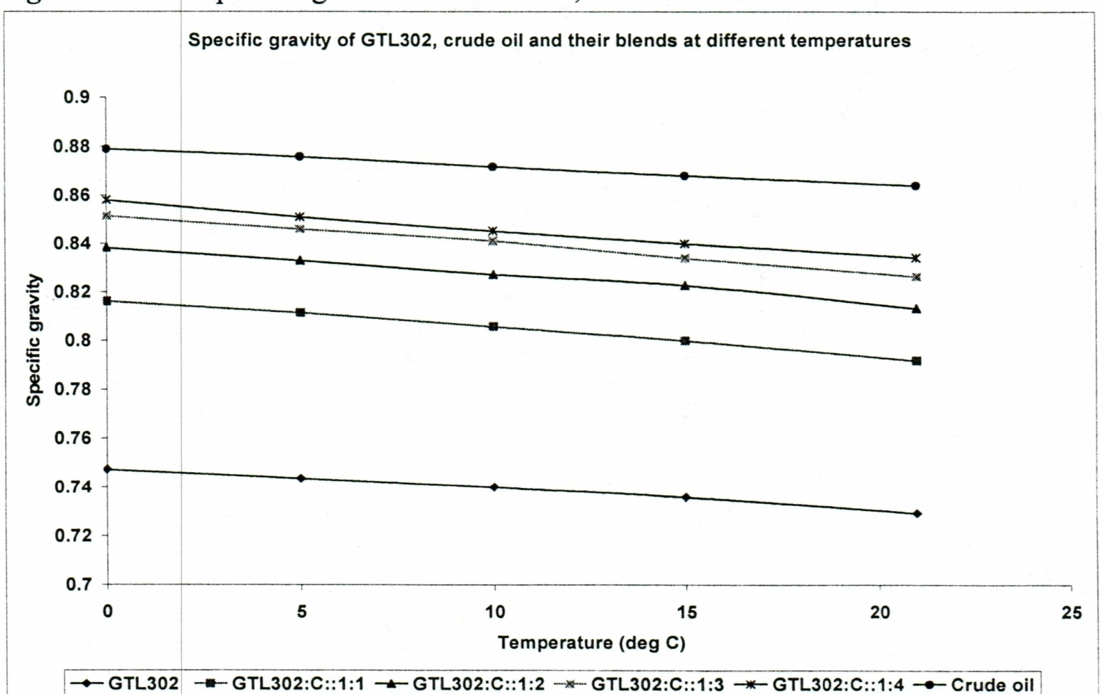

Figure 5.2 Specific gravities of GTL302, crude oil and their blends.

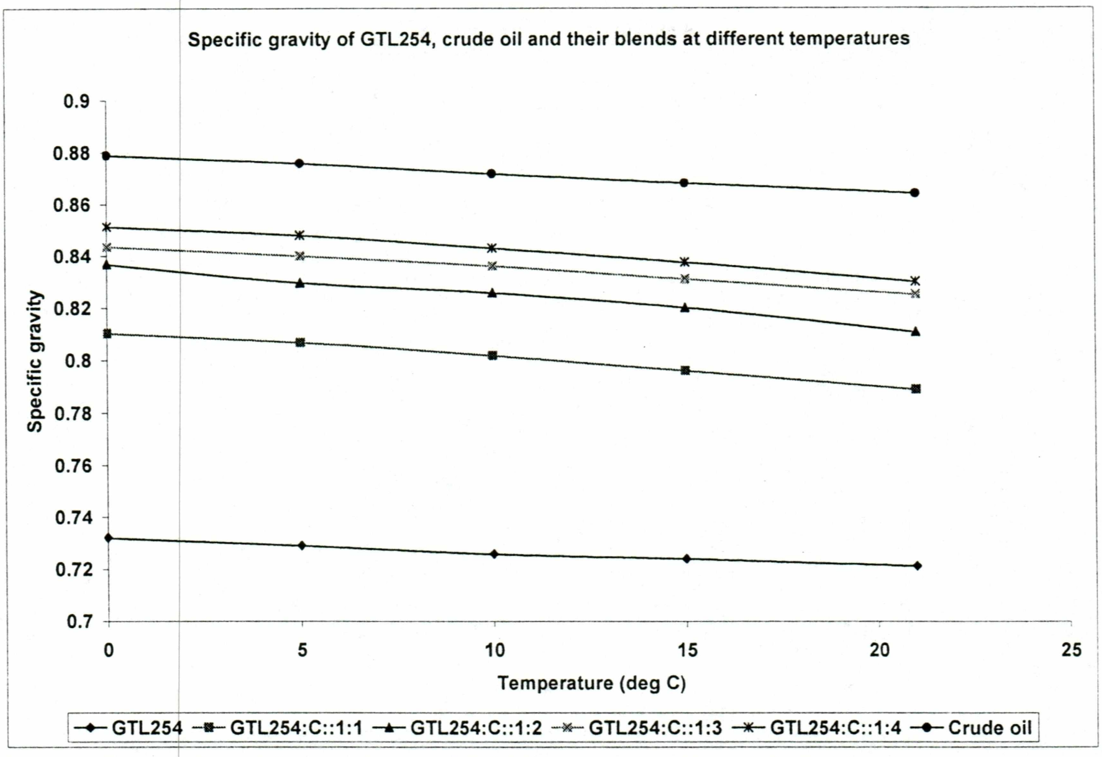

Figure 5.3 Specific gravities of GTL254, crude oil and their blends.

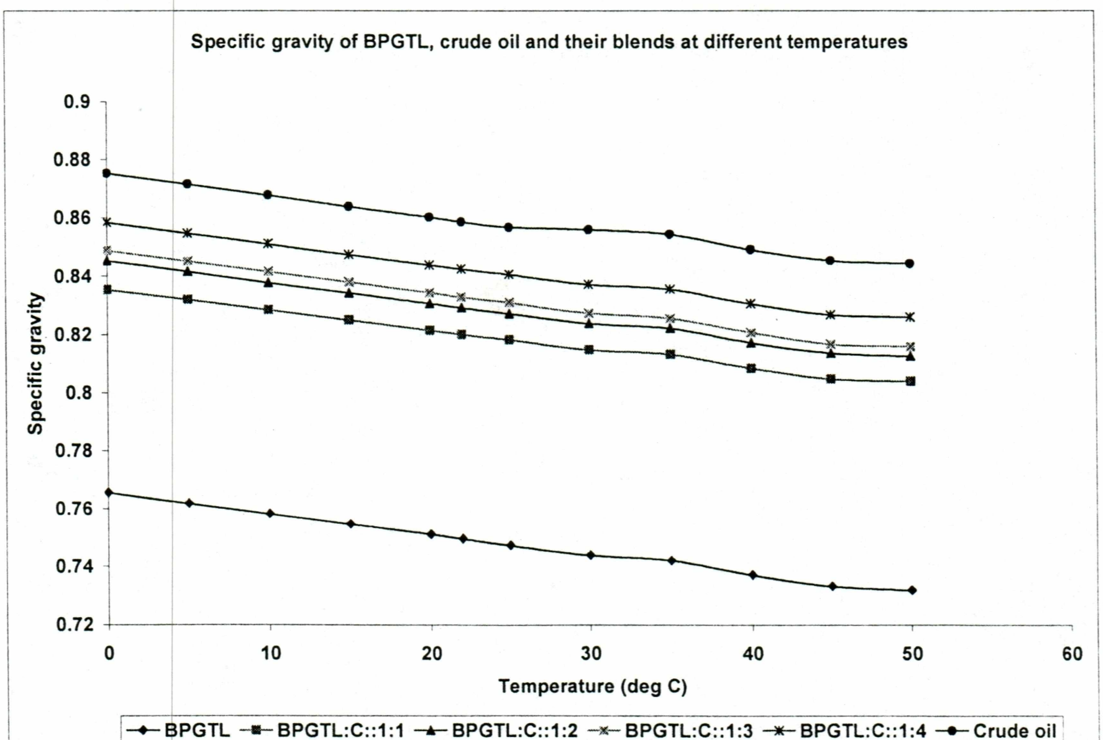

Figure 5.4 Specific gravities of BPGTL, crude oil and their blends.

It can be seen from the results of density measurements that BPGTL has higher densities at all temperatures than GTL344. Hence BPGTL is heavier than all the GTL cuts.

5.2 RHEOLOGY AND VISCOSITY MEASUREMENTS

Brookfield's cone plate viscometer was used to find the viscosity of the fluid samples. The readings within the 10% to 100% torque range were accepted for accuracy as mentioned in the manual. For viscous fluids and at lower temperatures the 100% torque is achieved at comparitively lower shear rates. Hence less data points are obtained at low temperatures as well as for viscous fluids. These shear stress values are plotted against shear rate values. Regression coefficient (R^2) is used to decide the best fit curve. Flow behavior parameters n & k and viscosities are determined with the help of these curves. GTL, crude oil and their blends are then classified as Newtonian or non Newtonian fluids based on the best fits and values of n and k.

5.2.1 Crude oil

TAPS crude oil shows Newtonian behavior at higher temperatures (>20 deg C). At lower temperatures it shows Bingham plastic behavior with some yield point. Viscosity of crude oil is determined by the slope of the shear stress vs. shear rate plot. The experimental results are plotted on the Cartesian graph. The representative rheograms at temperatures 50 deg C, 30 deg C and 10 deg C are shown in figures 5.5 through 5.7. The classification of crude oil behavior based on temperature is tabulated in table 5.5. The table also summarizes the absolute viscosities for Newtonian behavior and plastic viscosities (PV) and the yield values for Bingham plastic behavior.

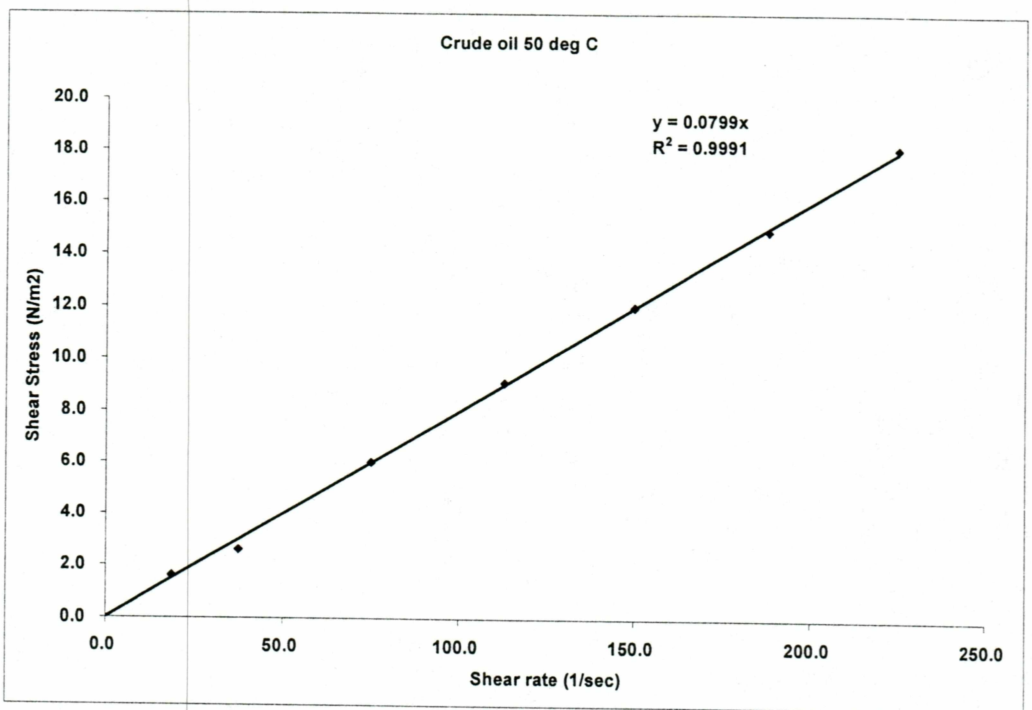

Figure 5.5 Rheogram for Crude Oil at 50 deg C

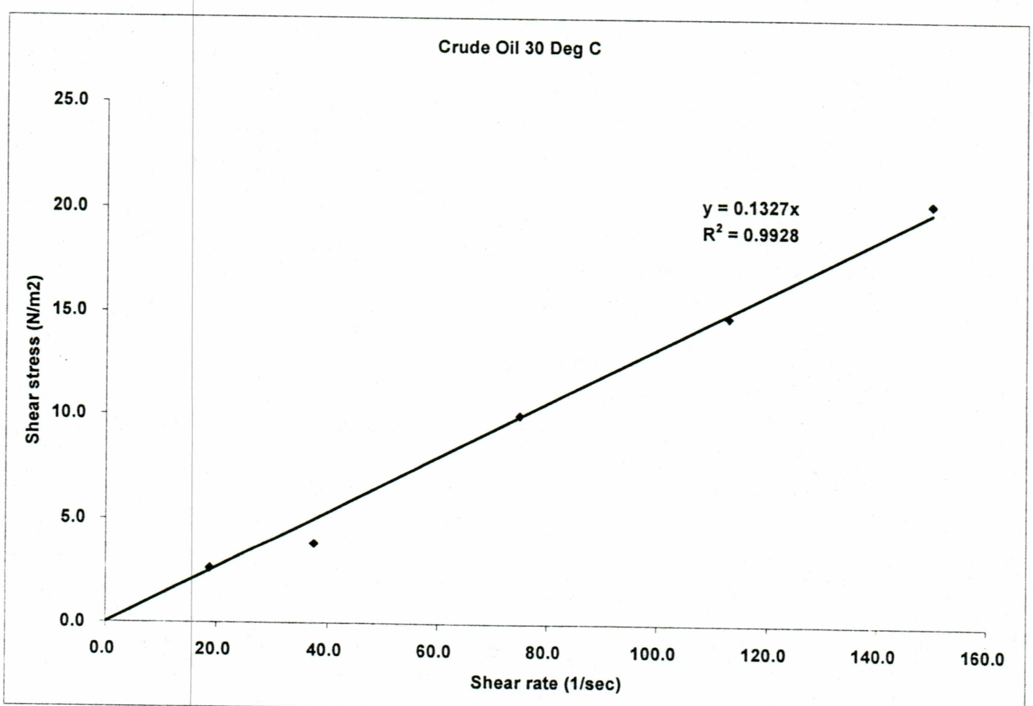

Figure 5.6 Rheogram for Crude oil at 30 deg C

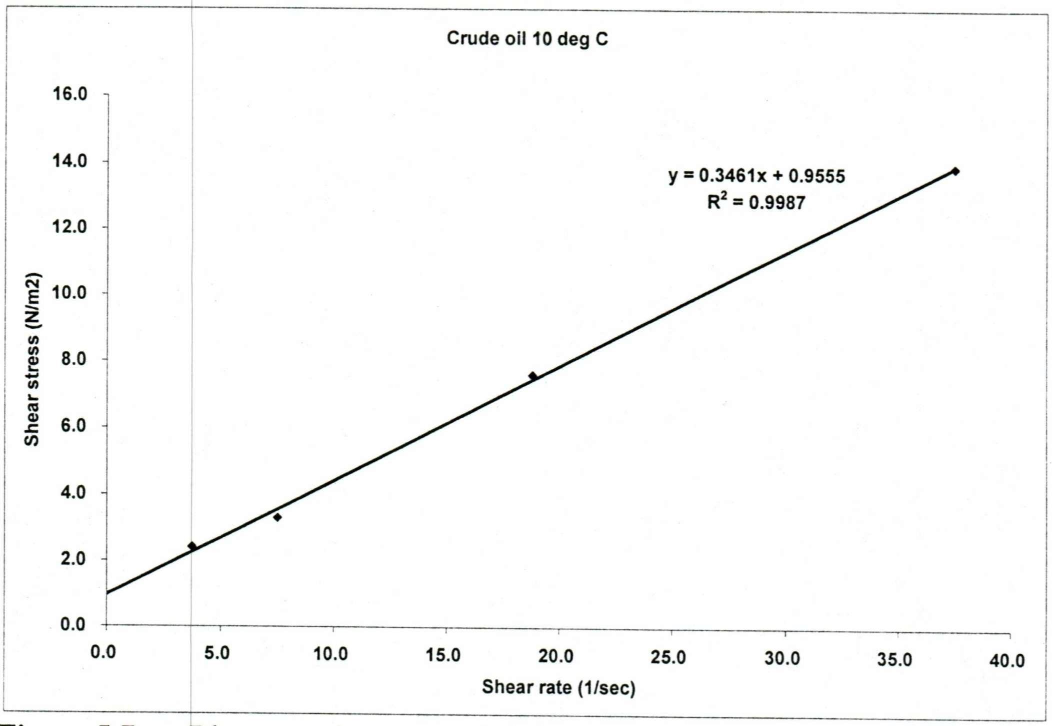

Figure 5.7 Rheogram for Crude oil at 10 deg C

Table 5.5 Flow behavior of crude oil, its viscosity and yield point at different temperatures.

Fluid	Temperature		Flow Behavior	abs viscosity/PV	YP
	deg C	deg F		centipoise	$N.s^n/m^2$
Crude oil	50	122	Newtonian	7.99	
	45	113	Newtonian	8.97	
	40	104	Newtonian	10.06	
	35	95	Newtonian	11.39	
	30	86	Newtonian	13.27	
	25	77	Newtonian	15.12	
	20	68	Newtonian	18.35	
	15	59	Bingham	25.54	0.3991
	10	50	Bingham	34.61	0.9555
	5	41	Bingham	56.21	1.3611
	0	32	Bingham	109.84	1.9066
	-5	23	Bingham	318.16	2.2934

5.2.2 BPGTL

From the experimental results, shear stress and shear rate of BP GTL field sample were plotted on the Cartesian graph to get the rheograms. Log-log graphs were plotted in order to find out n and k. From the nature of the curve and values of n (<1) it was concluded that GTL shows pseudoplastic behavior at all the temperatures in consideration. In order to validate this, using Fann viscometer an experiment was carried out at room temperature on GTL. From this experiment the value of n obtained was 0.534.

Instead of averaging the values of n and k for all shear rates, two regions were defined a) shear rate less than 375 1/sec (rps<357 1/sec) region and b) shear rate greater than 375 1/sec (rps>375 1/sec) region. On log-log plots best linear fits were drawn in these two regions to get the values of n and k. The slope of the fit gives 'n' while the intercept give 'logk' from which 'k' is found out. It can be seen from table 5.6 values of k of rps<375 1/sec region are greater than k values of rps>375 1/sec region which explains the shear thinning behavior. Values of n of rps<375 1/sec region are less than that of rps>375 1/sec region indicating dominating pseudoplastic behavior at lower shear rates. The n values of rps>375 1/sec region are closer to unity which is due to linearization of the shear stress shear rate curve. These two regions are prominent at higher temperatures. But at lower temperatures (below 5 deg C) not many data points were available to differentiate in the two regions as mentioned above since only one or two data points above 375 rps were available before 100% torque was achieved at all these lower temperatures. Hence the two regions were merged in one single region for temperatures below 5 deg C and only one value of n and k is given.

The representative rheograms and the log-log plots at temperatures 50 deg C, 30 deg C, 10 deg C and -10 deg C are shown in figures 5.8 through 5.11 and the n and k values are tabulated in table 5.6.

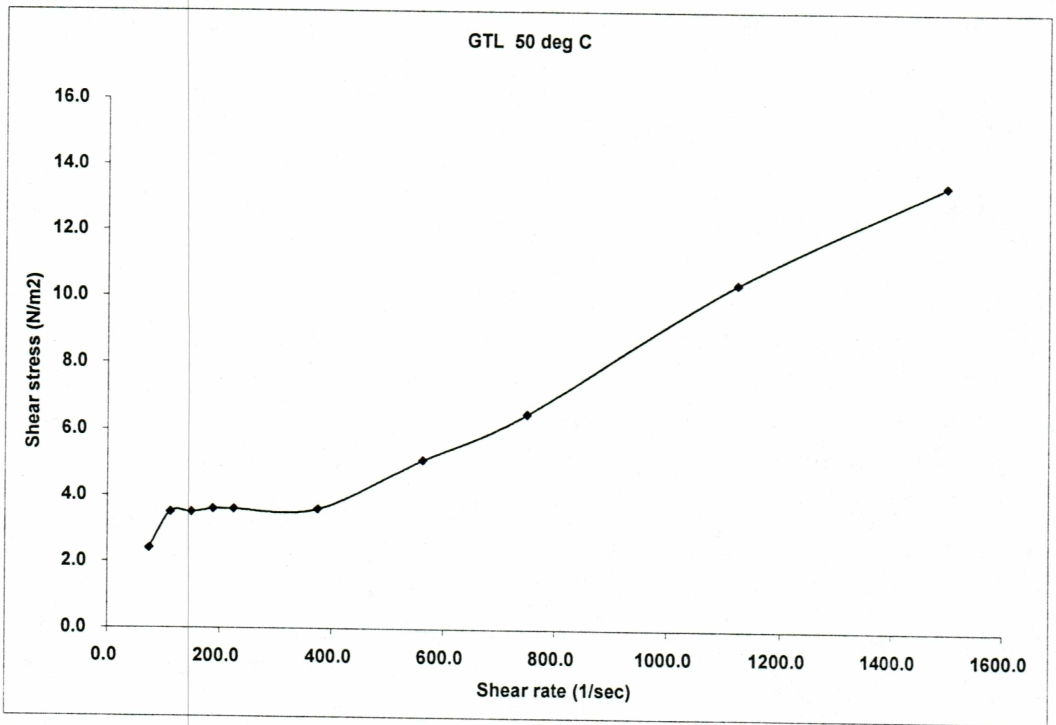

Figure 5.8a Rheogram for BPGTL at 50 deg C

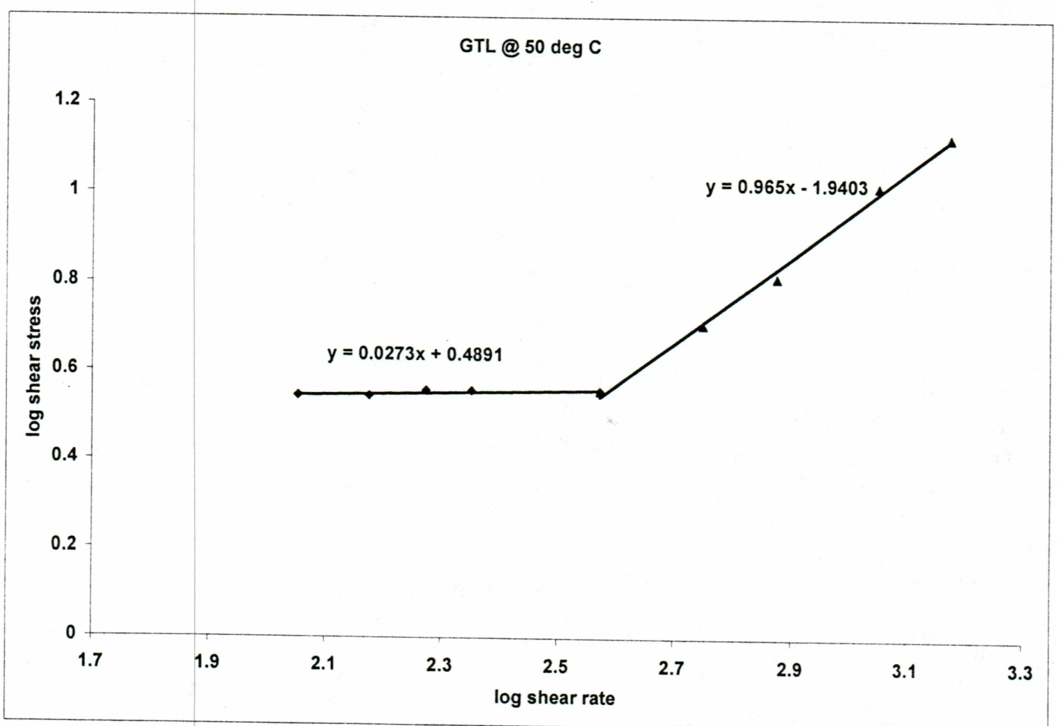

Figure 5.8b Log-log plot for BPGTL to find out n and k values (at 50 deg C)

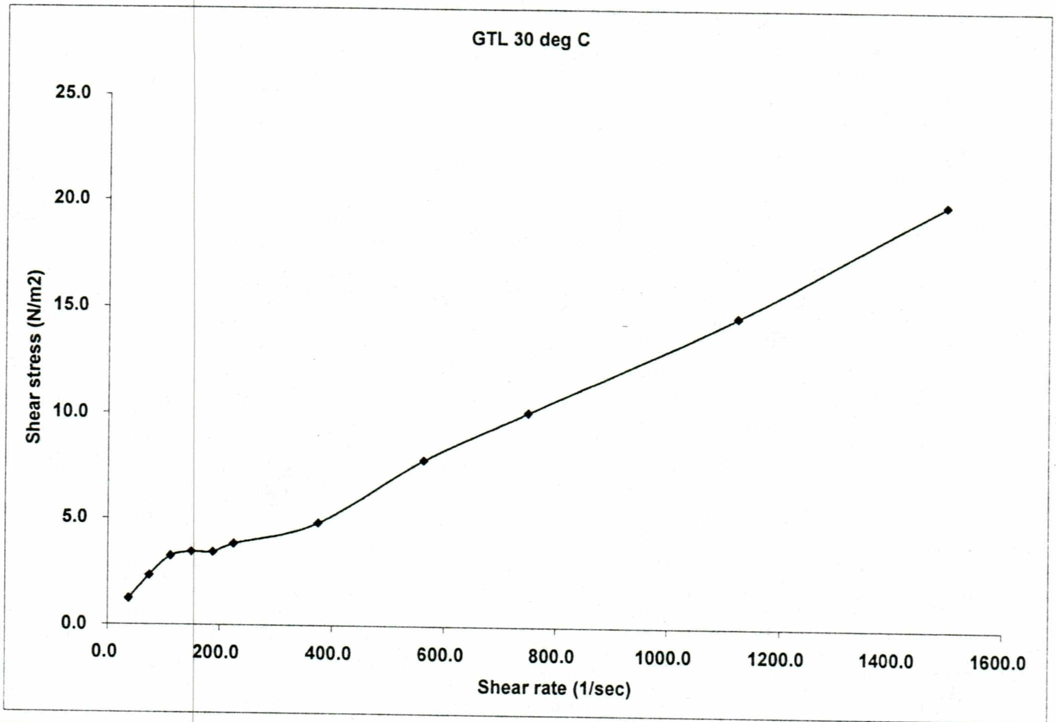

Figure 5.9a Rheogram for BPGTL at 30 deg C

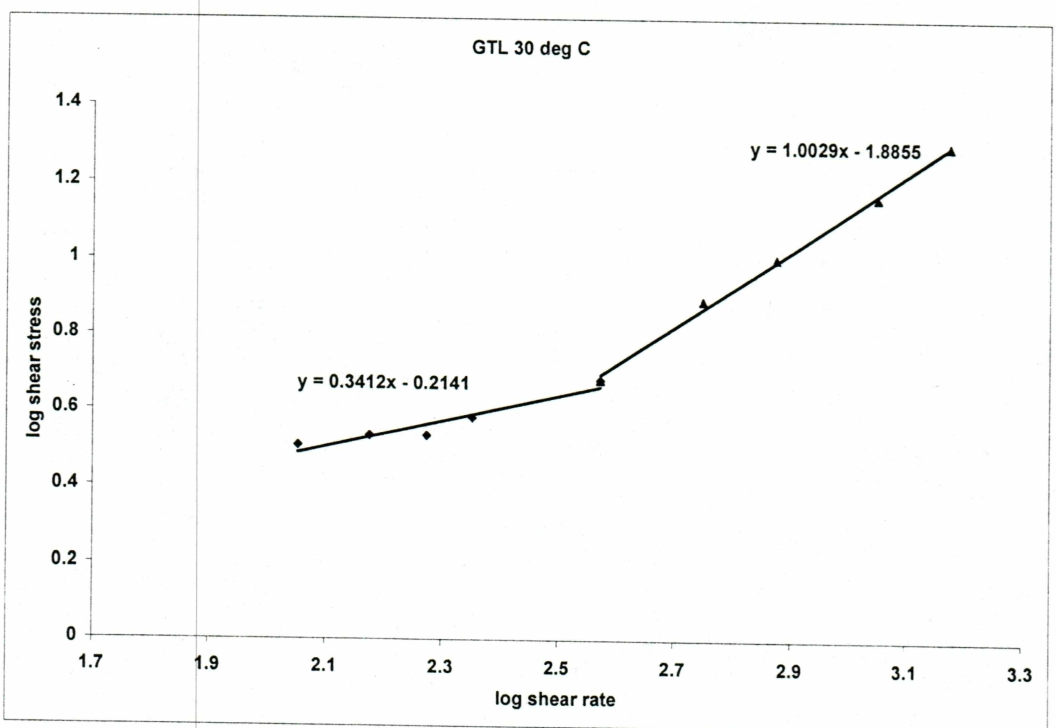

Figure 5.9b Log-log plot for BPGTL to find out n and k values (at 30 deg C)

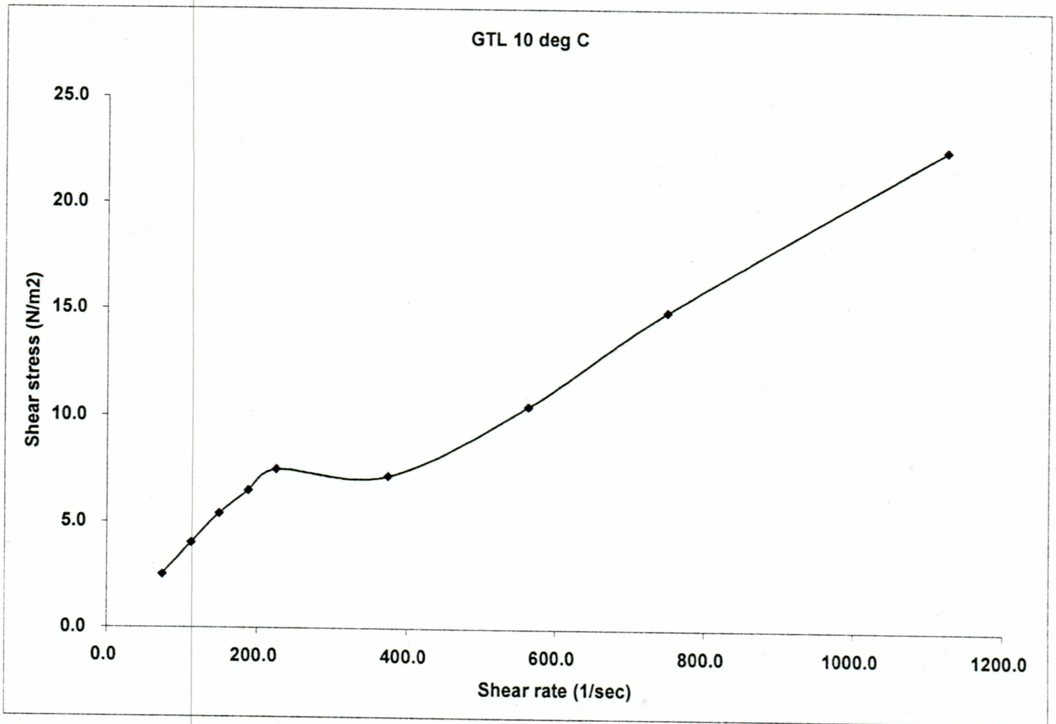

Figure 5.10a Rheogram for BPGTL at 10 deg C

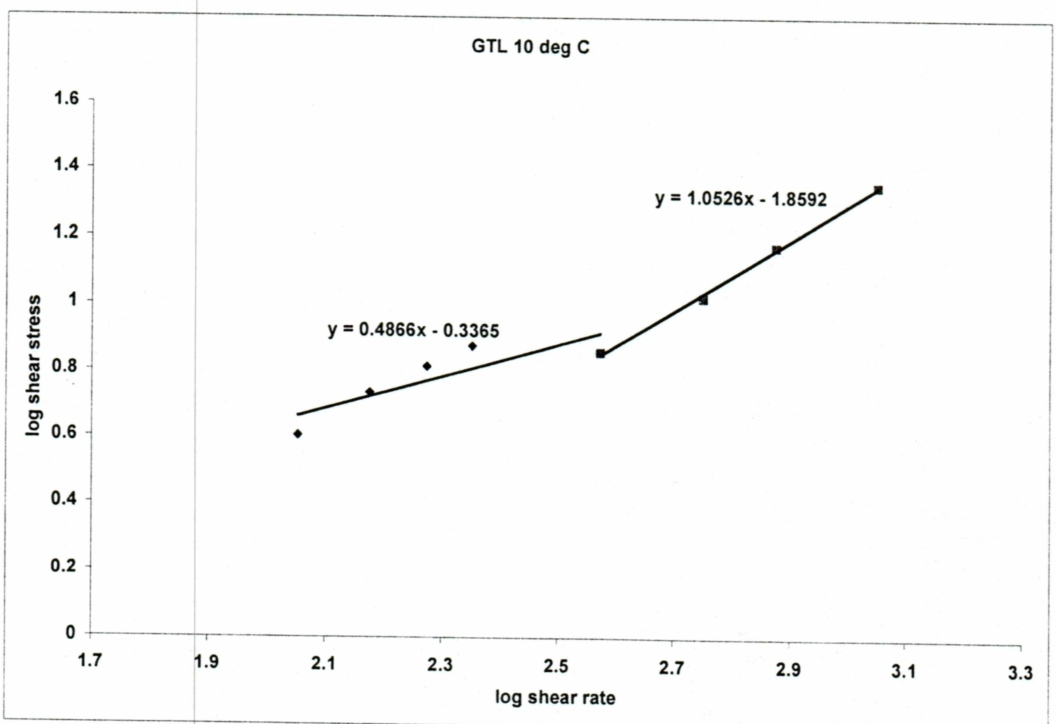

Figure 5.10b Log-log plot for BPGTL to find out n and k values (at 10 deg C)

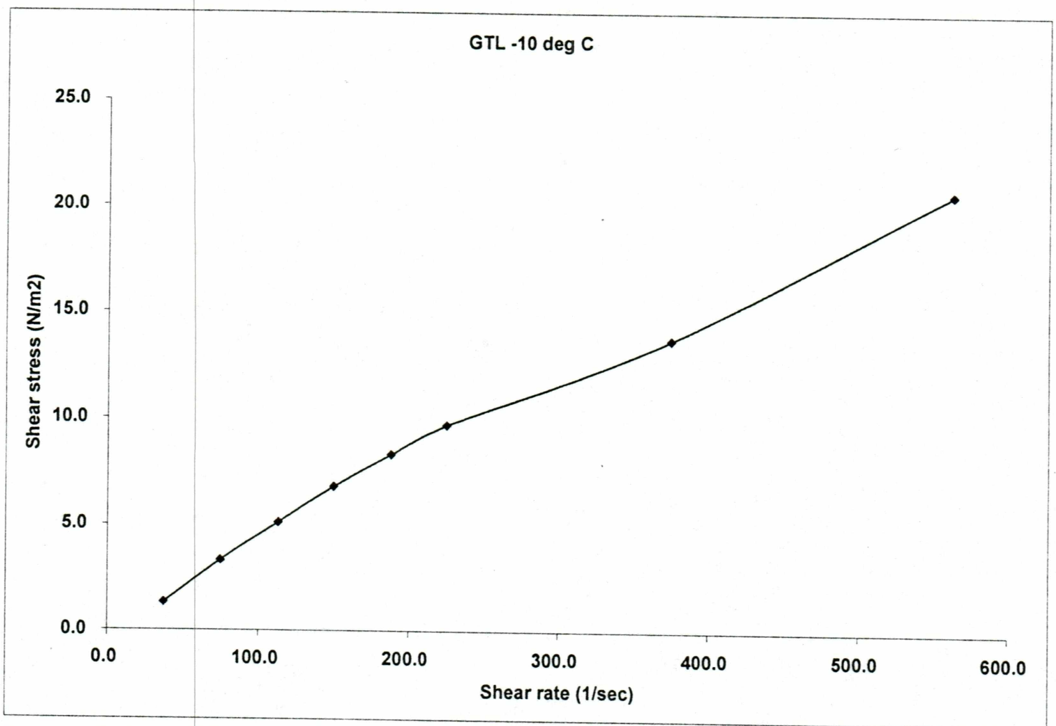

Figure 5.11a Rheogram for BPGTL at -10 deg C

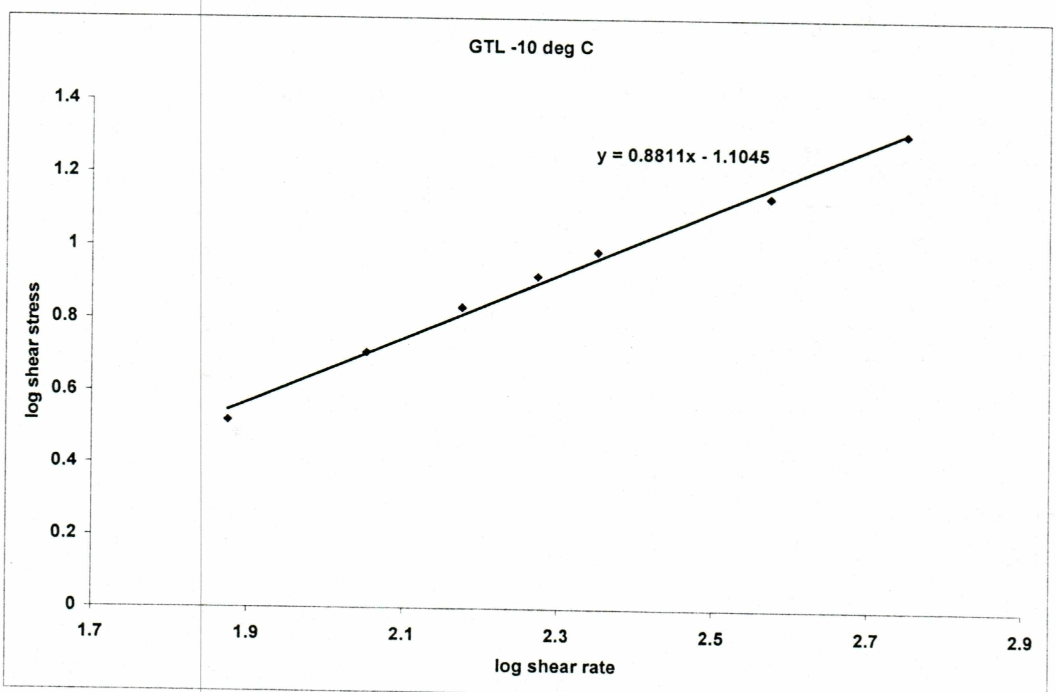

Figure 5.11b Log-log plot for BPGTL to find out n and k values (at -10 deg C)

Table 5.6 Flow behavior parameters for BPGTL.

Fluid	Temperature		Behavior	n		k ($lbf.s^n/100ft^2$)	
	deg C	deg F		rps < 375 1/sec	rps > 375 1/sec	rps < 375 1/sec	rps > 375 1/sec
BP GTL	50	122	Pseudoplastic	0.0273	0.965	6.4407	0.0240
	45	113	Pseudoplastic	0.0573	0.9956	6.0762	0.0218
	40	104	Pseudoplastic	0.1291	1.0716	3.8863	0.0138
	35	95	Pseudoplastic	0.2747	1.0195	1.7875	0.0223
	30	86	Pseudoplastic	0.3412	1.0029	3.4193	0.0272
	25	77	Pseudoplastic	0.4389	1.0316	0.7489	0.0243
	22	71.6	Pseudoplastic	0.3948	0.9584	1.1149	0.0407
	20	68	Pseudoplastic	0.5015	0.9635	0.6128	0.0417
	15	59	Pseudoplastic	0.4302	0.9797	1.4974	0.0432
	10	50	Pseudoplastic	0.4866	1.0526	0.9624	0.0458
	5	41	Pseudoplastic	0.7018	0.9571	0.3404	0.0628
	0	32	Pseudoplastic	0.8302		0.0653	
	-5	23	Pseudoplastic	0.8108		0.2159	
	-10	14	Pseudoplastic	0.8811		0.1642	
	-15	5	Pseudoplastic	0.9750		0.1158	
	-20	-4	Pseudoplastic	0.8783		0.2262	

5.2.3 BPGTL/Crude Oil Blends

Blends of GTL and crude oil show Newtonian, pseudoplastic and Bingham Plastic behavior depending on the temperature. At higher temperatures (above room temperature) pseudoplastic behavior is observed, at intermediate temperatures (around room temperature) Newtonian behavior can be seen whereas at lower temperatures (around 0 deg C and below) Bingham plastic behavior is noted. This is summarized in table 5.7 through 5.10.

Table 5.7 Flow behavior and related parameters for 1:1 BPGTL/Crude Oil blend

Fluid	Temperature		Behavior	n	K	Viscosity/PV	YP
	deg C	deg F			$lbf.s^n/100ft^2$	cp	N/m^2
1:1::GTL :crude oil	50	122	Pseudoplastic	0.8528	0.1645		
	45	113	Pseudoplastic	0.8590	0.1711		
	40	104	Pseudoplastic	0.8946	0.1558		
	35	95	Pseudoplastic	0.8933	0.1693		
	30	86	Pseudoplastic	0.9250	0.1570		
	25	77	Pseudoplastic	0.9728	0.1343		
	20	68	Pseudoplastic	0.9879	0.1329		
	15	59	Newtonian			7.36	
	10	50	Newtonian			8.73	
	5	41	Newtonian			10.76	
	0	32	Newtonian			13.96	
	-5	23	Bingham			18.79	0.5251
	-10	14	Bingham			27.14	0.8679
	-15	5	Bingham			47.47	0.3387
	-20	-4	Bingham			77.67	0.9536

Table 5.8 Flow behavior and related parameters for 1:2 BPGTL/Crude Oil blend

Fluid	Temperature		Behavior	n	K	Viscosity/PV	YP
	deg C	deg F			$lbf.s^n/100ft^2$	cp	N/m^2
1:2::GTL :crude oil	50	122	Pseudoplastic	0.8573	0.1741		
	45	113	Pseudoplastic	0.8397	0.2132		
	40	104	Pseudoplastic	0.8268	0.2459		
	35	95	Pseudoplastic	0.8494	0.2454		
	30	86	Pseudoplastic	0.9335	0.1776		
	25	77	Pseudoplastic	0.9754	0.1554		
	20	68	Newtonian			6.54	
	15	59	Newtonian			7.60	
	10	50	Newtonian			8.82	
	5	41	Newtonian			10.80	
	0	32	Newtonian			14.63	
	-5	23	Bingham			18.95	0.4401
	-10	14	Bingham			27.98	0.9164
	-15	5	Bingham			43.33	1.0931
	-20	-4	Bingham			82.92	2.2153

Table 5.9 Flow behavior and related parameters for 1:3 BPGTL/Crude Oil blend

Fluid	Temperature		Behavior	n	K	Viscosity/PV	YP
	deg C	deg F			lbf.s^n/100ft^2	cp	N/m^2
1:3::GTL :crude oil	50	122	Pseudoplastic	0.9225	0.1226		
	45	113	Pseudoplastic	0.9218	0.1385		
	40	104	Pseudoplastic	0.9482	0.1330		
	35	95	Pseudoplastic	0.9682	0.1363		
	30	86	Newtonian			6.27	
	25	77	Newtonian			6.88	
	22	71.6	Newtonian			7.04	
	20	68	Newtonian			7.31	
	15	59	Newtonian			8.58	
	10	50	Newtonian			11.17	
	5	41	Newtonian			14.44	
	0	32	Bingham			18.55	0.3180
	-5	23	Bingham			27.08	0.0027
	-10	14	Bingham			33.71	2.4322
	-15	5	Bingham			57.49	2.4164
	-20	-4	Bingham			81.76	5.1775

Table 5.10 Flow behavior and related parameters for 1:4 BPGTL/Crude Oil blend

Fluid	Temperature		Behavior	n	K	Viscosity/PV	YP
	deg C	deg F			lbf.s^n/100ft^2	cp	N/m^2
1:4::GTL :crude oil	50	122	Pseudoplastic	0.8097	0.2917		
	45	113	Pseudoplastic	0.8954	0.2086		
	40	104	Pseudoplastic	0.9668	0.1645		
	35	95	Newtonian			7.47	
	30	86	Newtonian			8.47	
	25	77	Newtonian			9.43	
	22	71.6	Newtonian			9.49	
	20	68	Newtonian			13.05	
	15	59	Newtonian			16.15	
	10	50	Bingham			21.05	0.2891
	5	41	Bingham			28.44	1.1055
	0	32	Bingham			45.09	1.9808
	-5	23	Bingham			86.87	2.1609
	-10	14	Bingham			186.36	3.8637

5.2.3.1 Rheograms and log-log plots for BPGTL/Crude Oil Blend with 1:1 ratio

The representative rheograms and the log-log plots of 1:1 BPGTL/Crude Oil blend at temperatures 50 deg C, 30 deg C, 10 deg C and -10 deg C are shown in figures 5.12 through 5.15

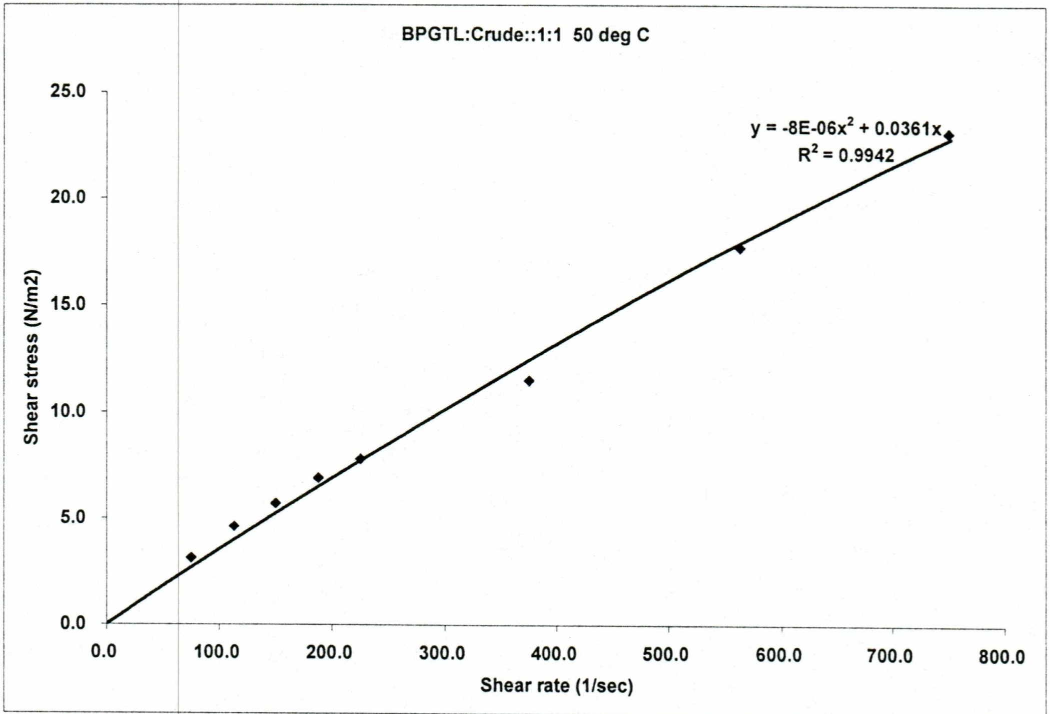

Figure 5.12a Rheogram for BPGTL/Crude Oil blend (1:1 ratio at 50 deg C)

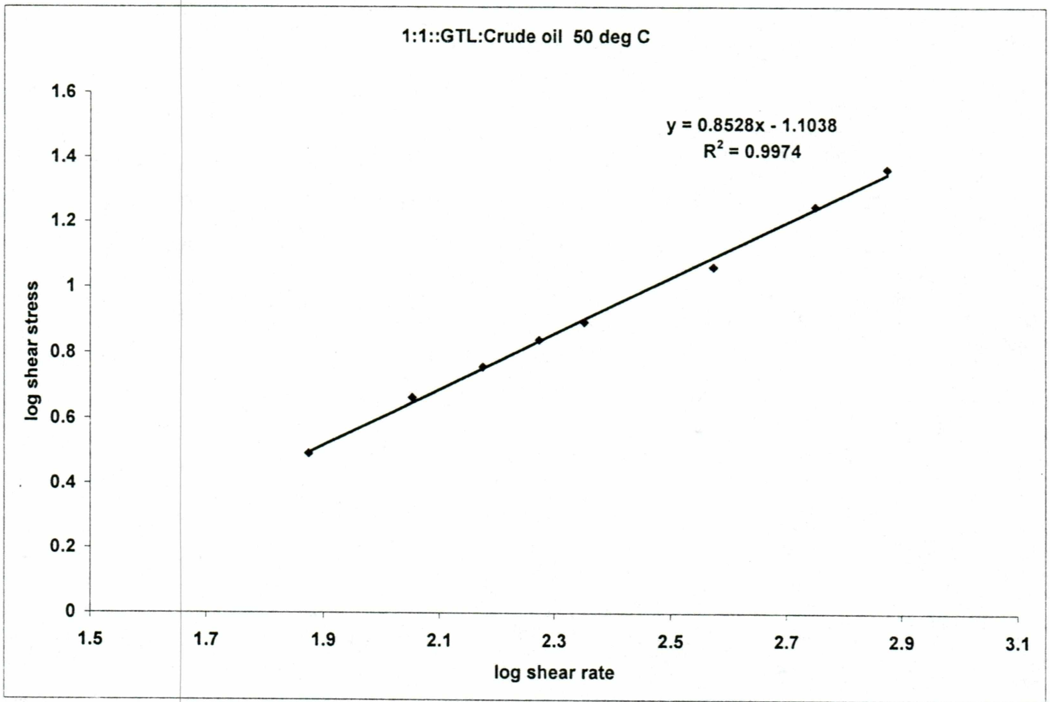

Figure 5.12b Log-log plot for BPGTL/Crude oil blend to find out n and k values (1:1 ratio at 50 deg C)

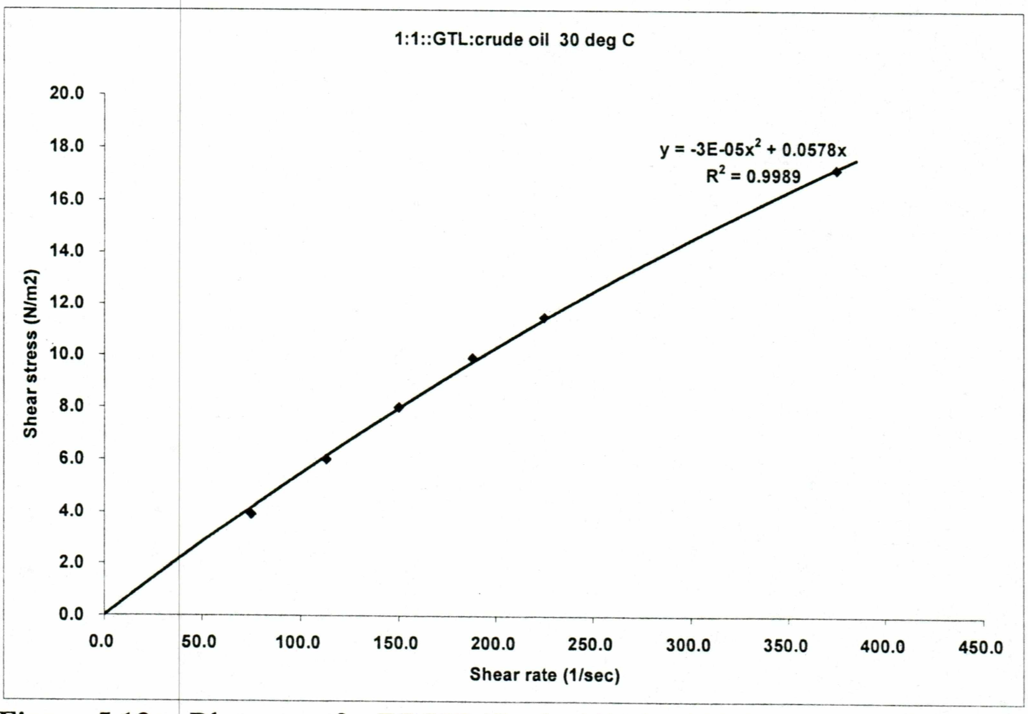

Figure 5.13a Rheogram for BPGTL/Crude Oil blend (1:1 ratio at 30 deg C)

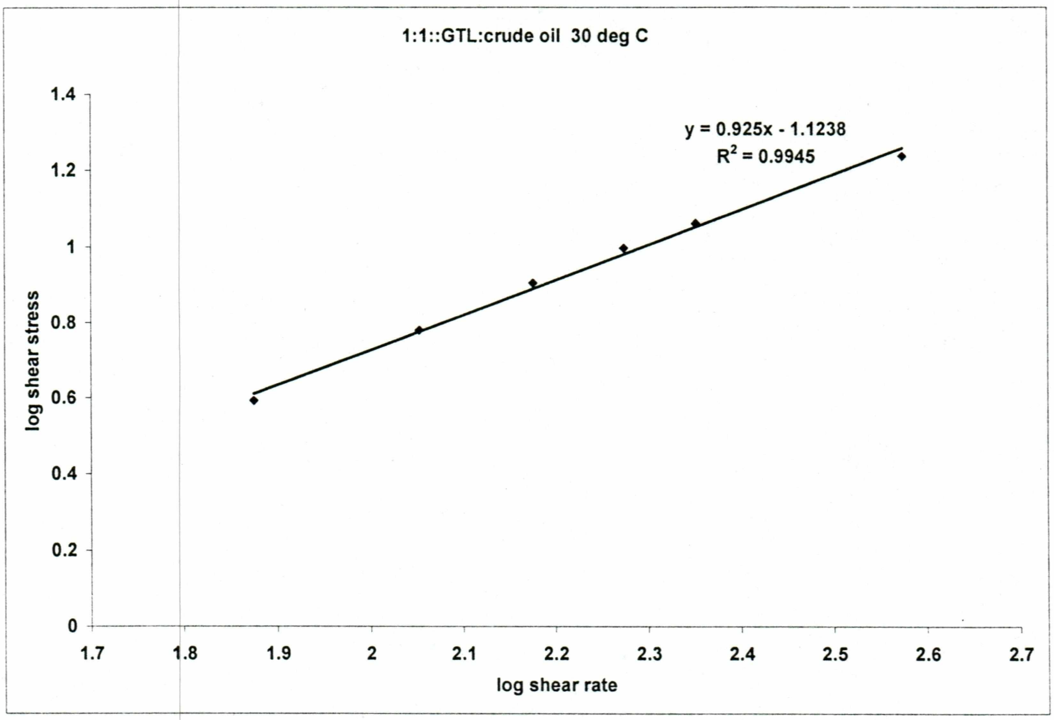

Figure 5.13b Log-log plot for BPGTL/Crude oil blend to find out n and k values (1:1 ratio at 30 deg C)

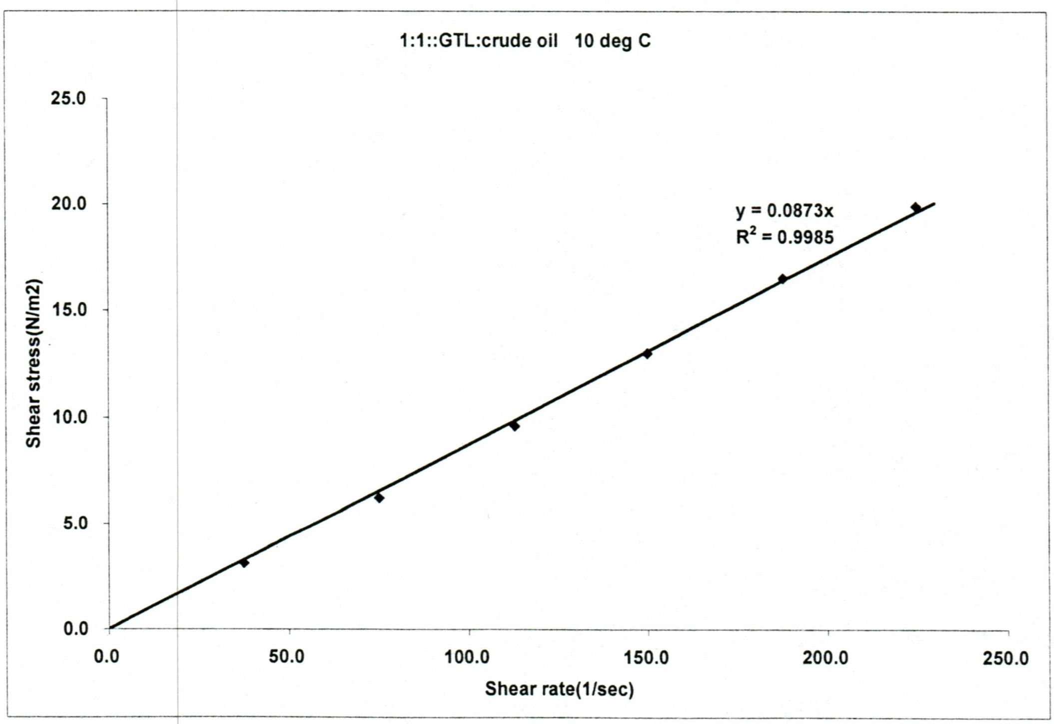

Figure 5.14 Rheogram for BPGTL/Crude Oil blend (1:1 ratio at 10 deg C)

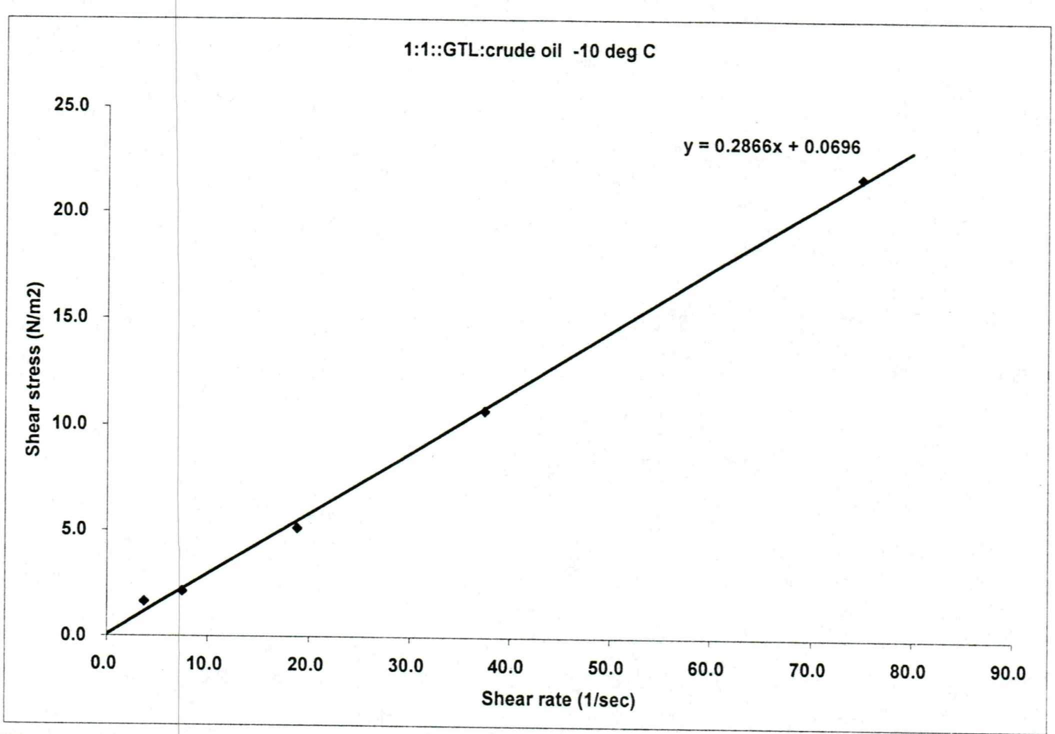

Figure 5.15 Rheogram for BPGTL/Crude Oil blend (1:1 ratio at -10 deg C)

5.2.3.2 Rheograms and log-log plots for BPGTL/Crude Oil Blend with 1:2 ratio

The representative rheograms and the log-log plots of 1:2 BPGTL/Crude Oil blend at temperatures 50 deg C, 30 deg C, 10 deg C and -10 deg C are shown in figures 5.16 through 5.19

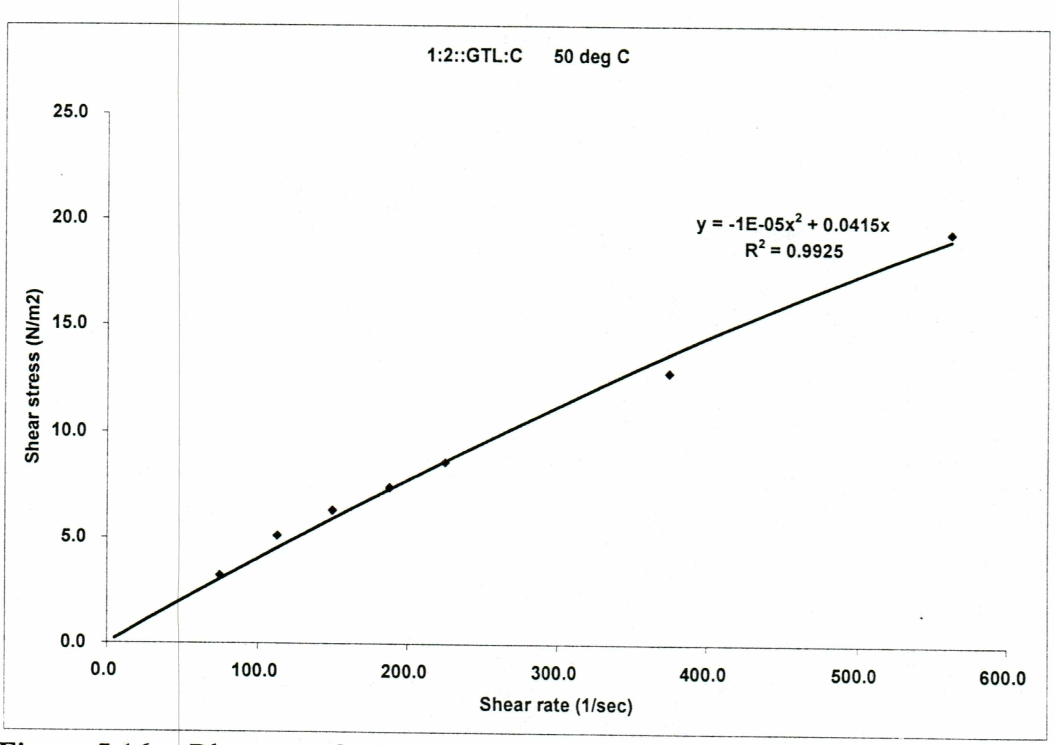

Figure 5.16a Rheogram for BPGTL/Crude Oil blend (1:2 ratio at 50 deg C)

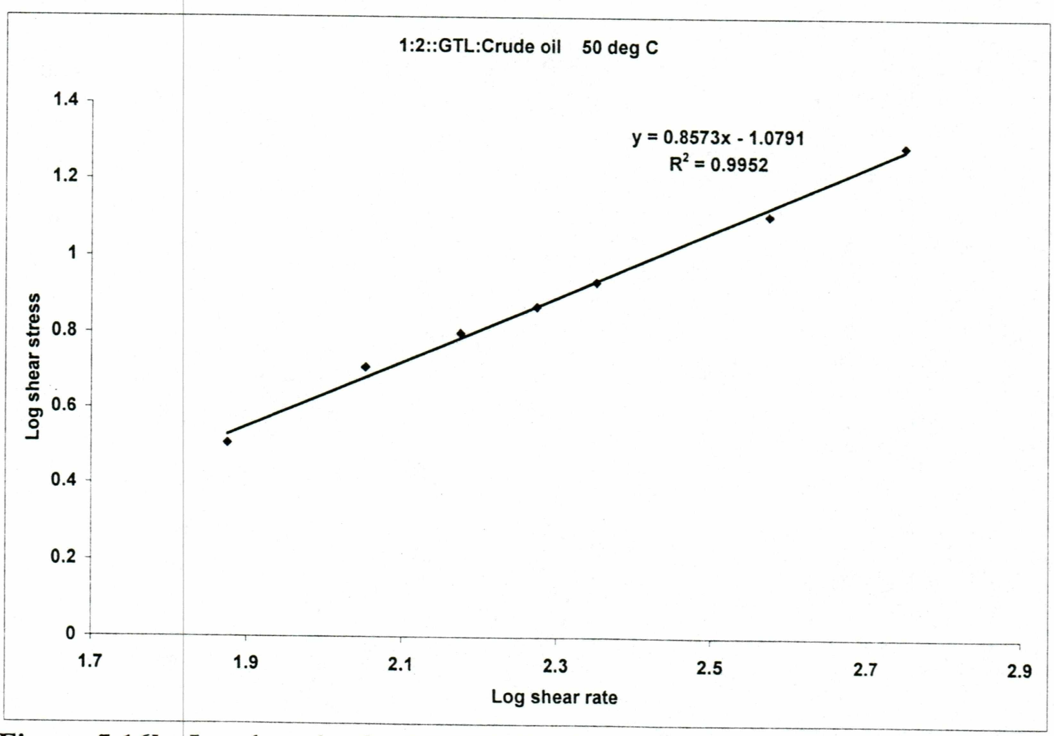

Figure 5.16b Log-log plot for BPGTL/Crude oil blend to find out n and k values (1:2 ratio at 50 deg C)

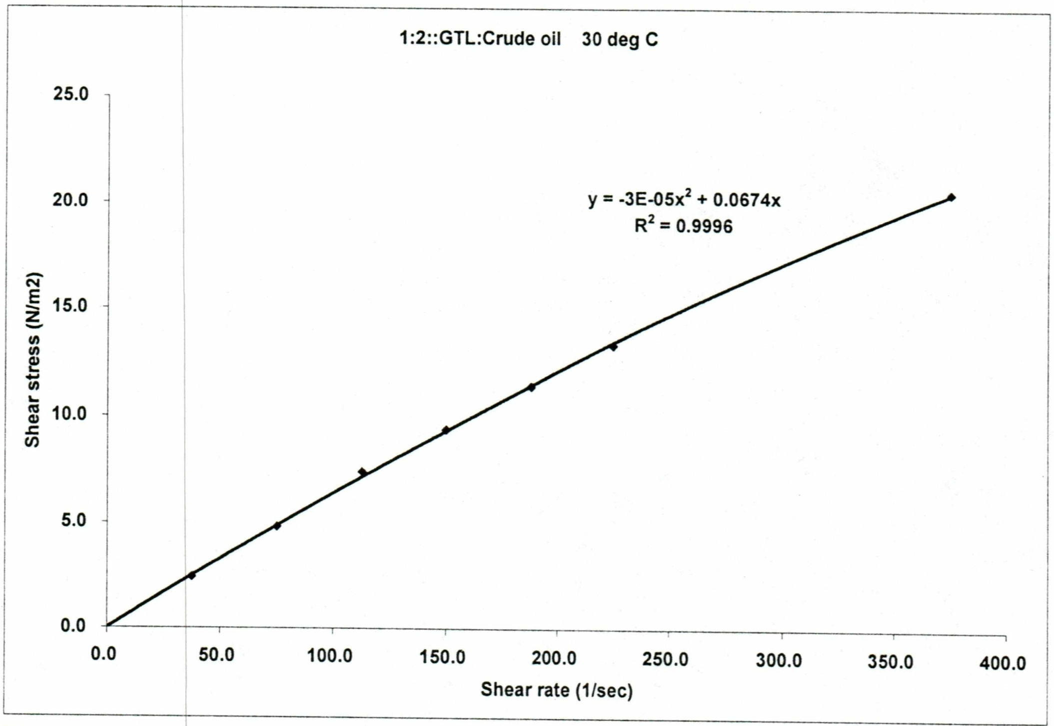

Figure 5.17a Rheogram for BPGTL/Crude Oil blend (1:2 ratio at 30 deg C)

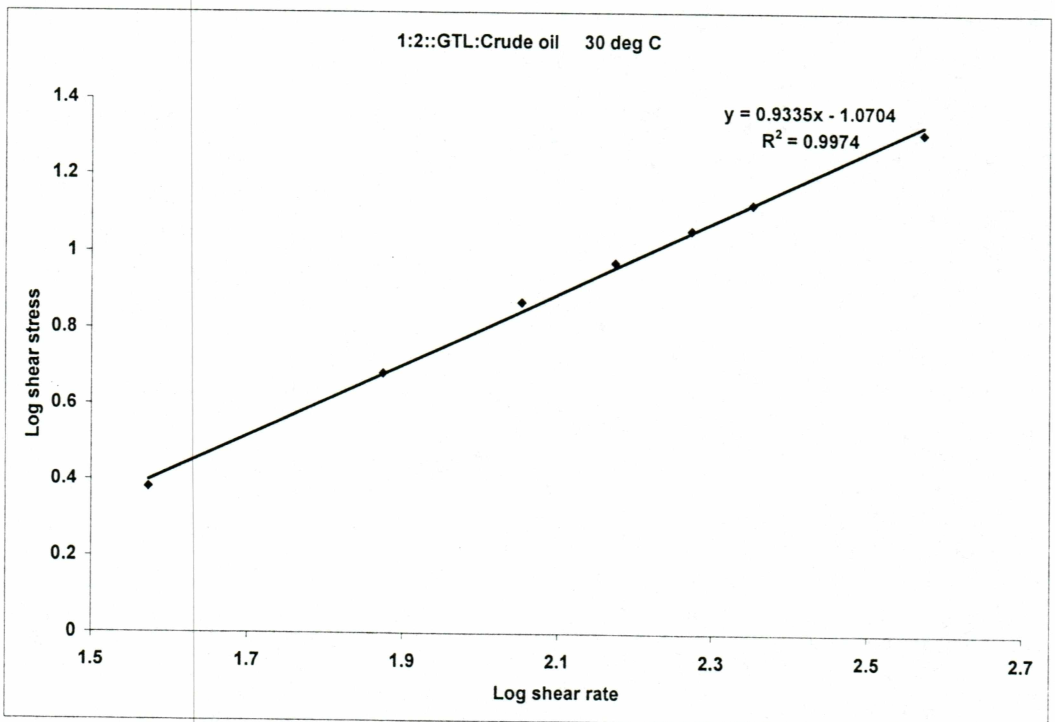

Figure 5.17b Log-log plot for BPGTL/Crude oil blend to find out n and k values (1:2 ratio at 30deg C)

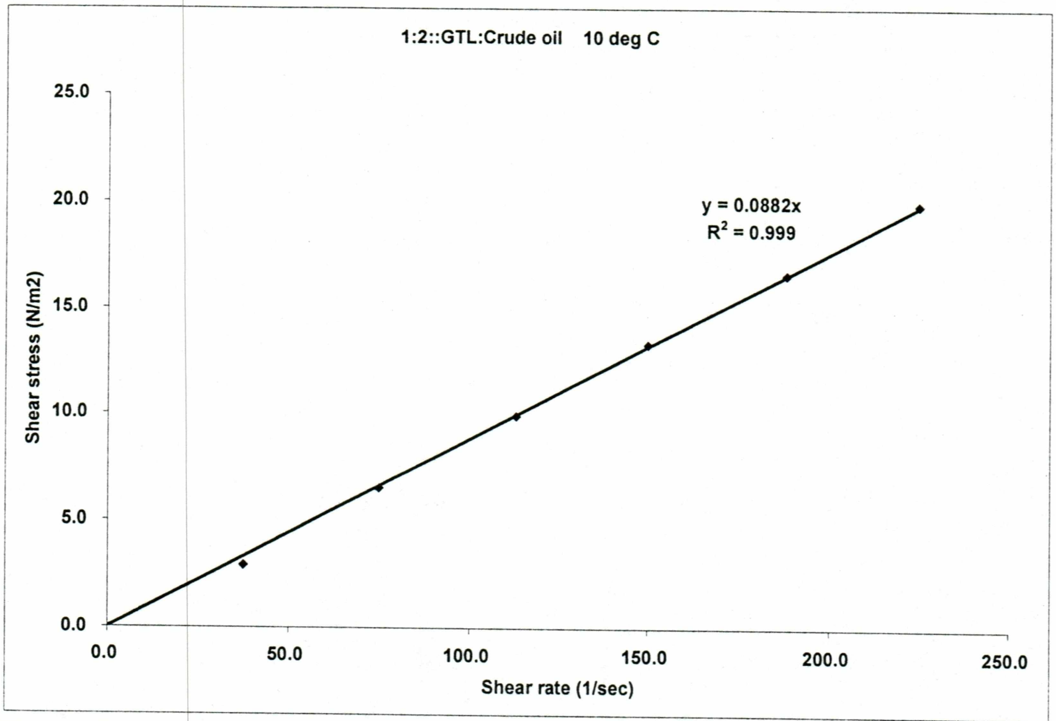

Figure 5.18 Rheogram for BPGTL/Crude Oil blend (1:2 ratio at 10 deg C)

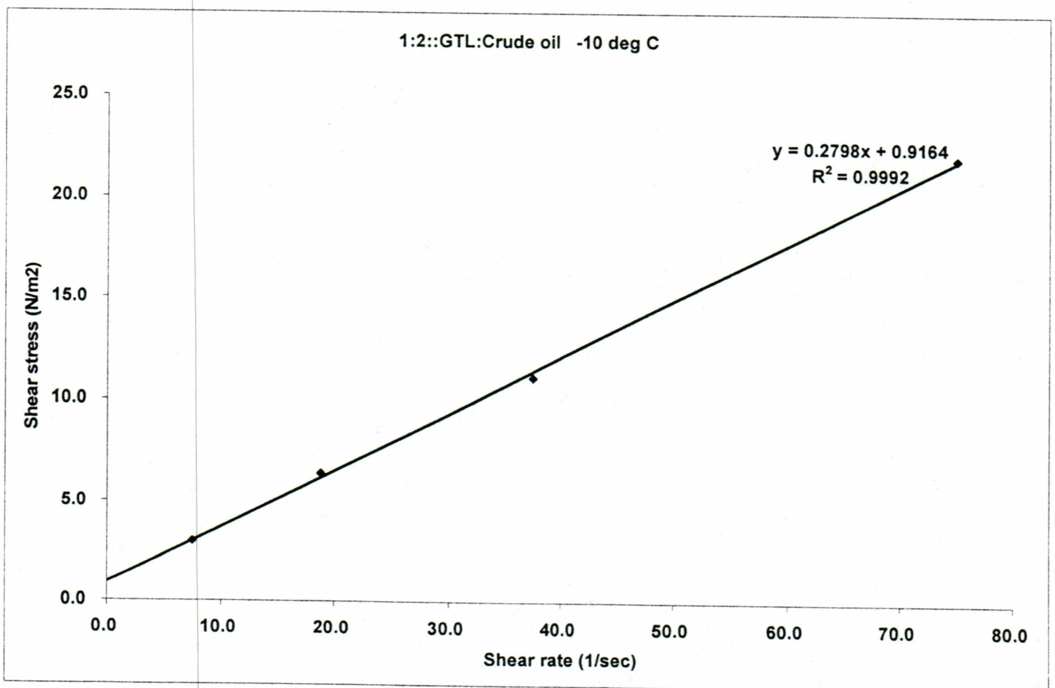

Figure 5.19 Rheogram for BPGTL/Crude Oil blend (1:2 ratio at -10 deg C)

5.2.3.3 Rheograms and log-log plots for BPGTL/Crude Oil Blend with 1:3 ratio

The representative rheograms and the log-log plots of 1:3 BPGTL/Crude Oil blend at temperatures 50 deg C, 30 deg C, 10 deg C and -10 deg C are shown in figures 5.20 through 5.23.

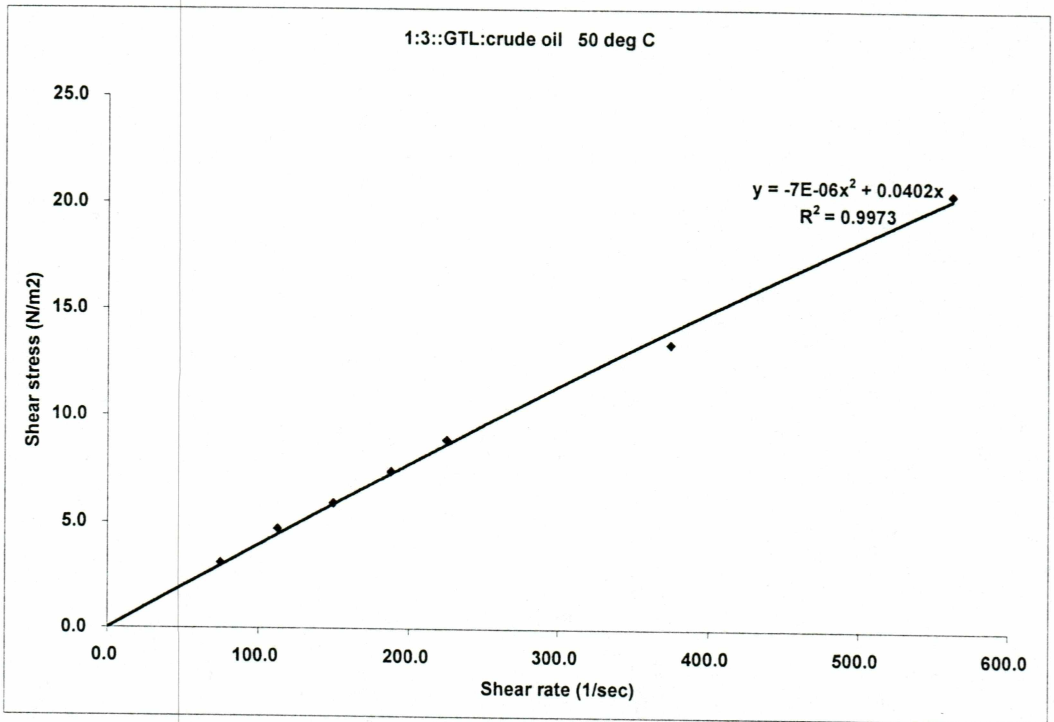

Figure 5.20a Rheogram for BPGTL/Crude Oil blend (1:3 ratio at 50 deg C)

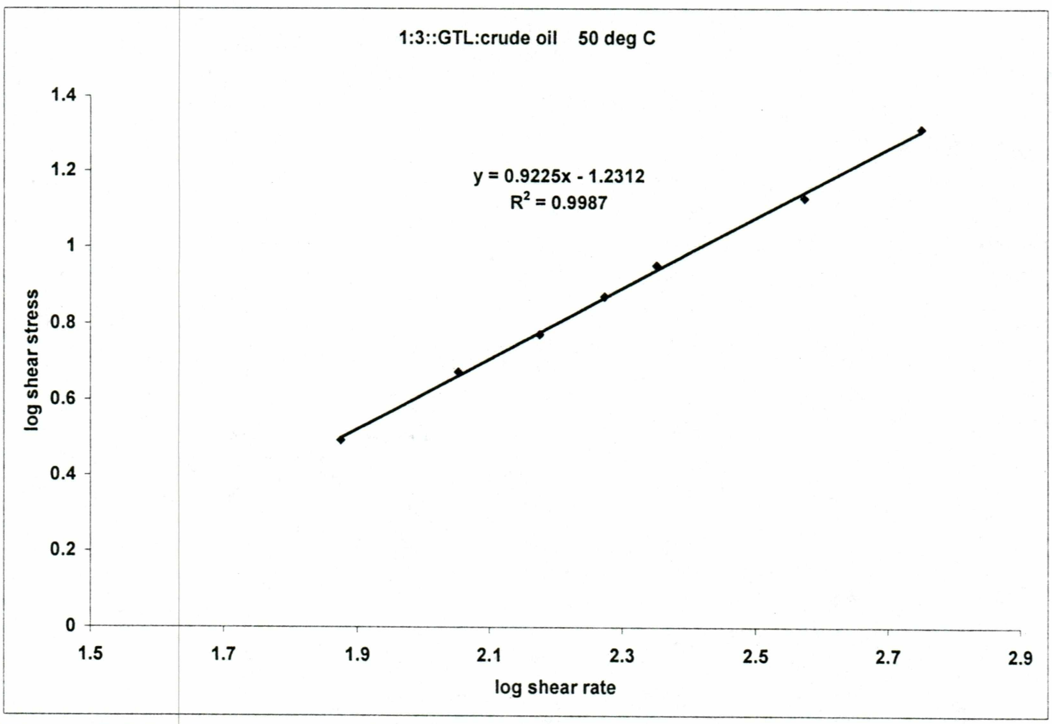

Figure 5.20b Log-log plot for BPGTL/Crude oil blend to find out n and k values (1:3 ratio at 50deg C)

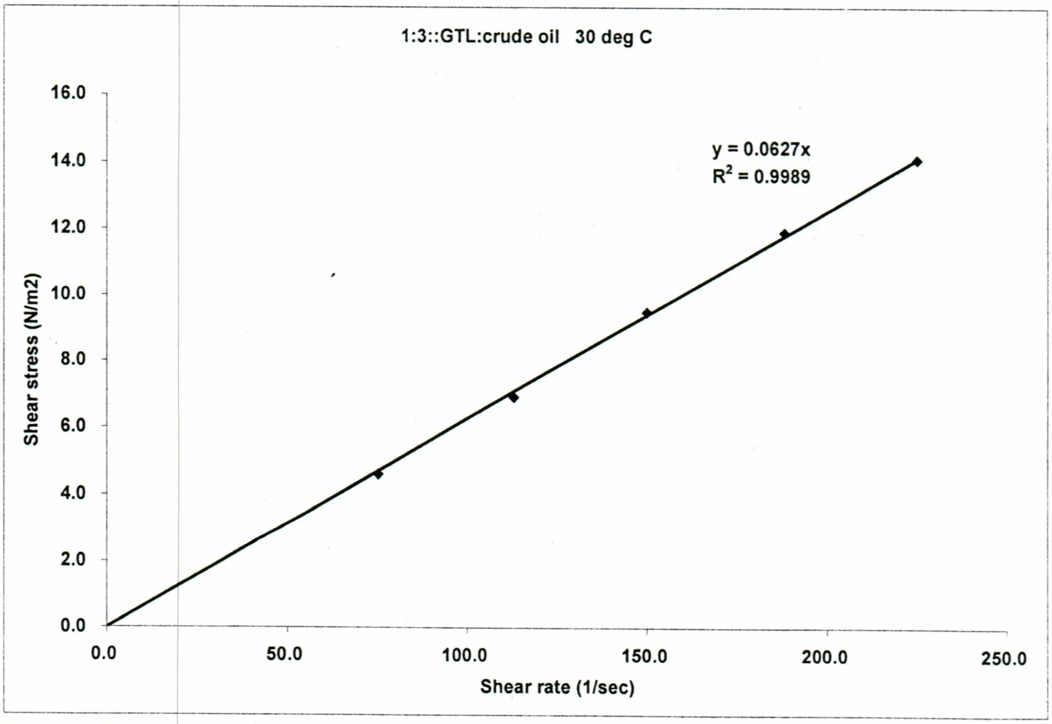

Figure 5.21 Rheogram for BPGTL/Crude Oil blend (1:3 ratio at 30 deg C)

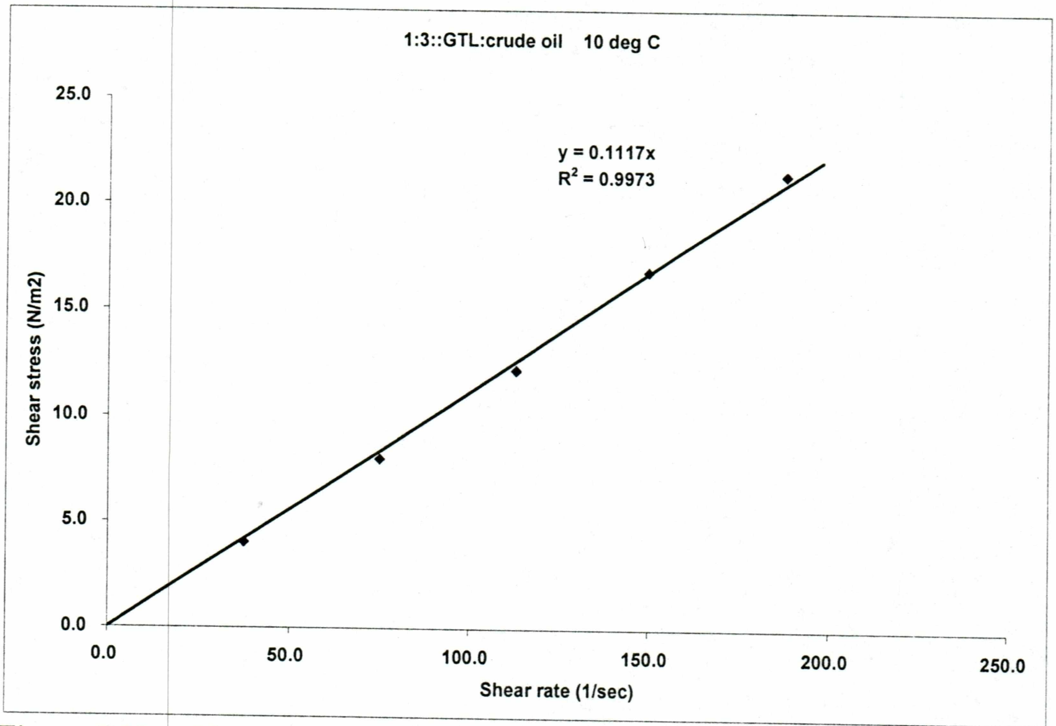

Figure 5.22 Rheogram for BPGTL/Crude Oil blend (1:3 ratio at 10 deg C)

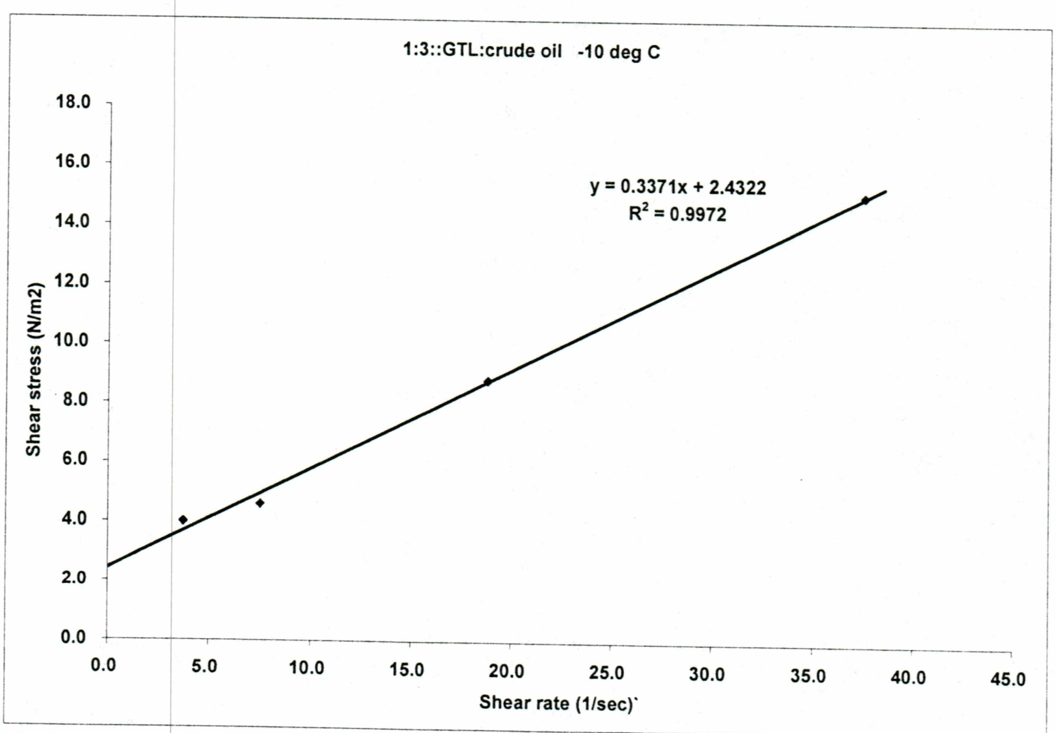

Figure 5.23 Rheogram for BPGTL/Crude Oil blend (1:3 ratio at -10 deg C)

5.2.3.4 Rheograms and log-log plots for BPGTL/Crude Oil Blend with 1:4 ratio

The representative rheograms and the log-log plots of 1:4 BPGTL/Crude Oil blend at temperatures 50 deg C, 30 deg C, 10 deg C and -10 deg C are shown in figures 5.24 through 5.27.

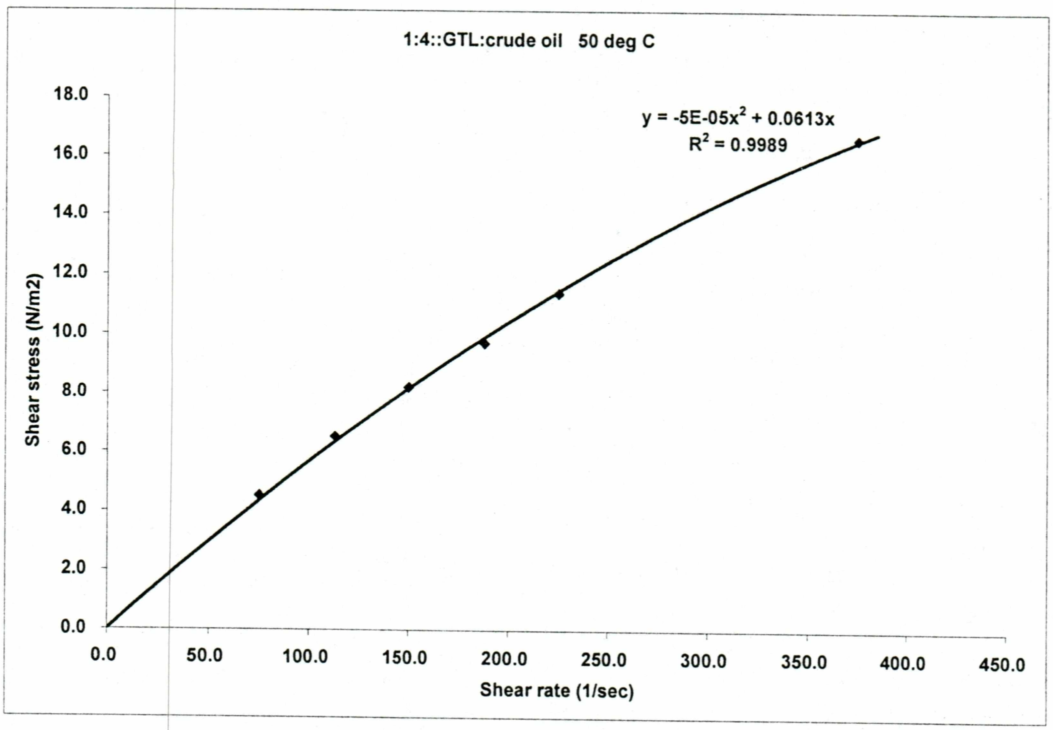

Figure 5.24a Rheogram for BPGTL/Crude Oil blend (1:4 ratio at 50 deg C)

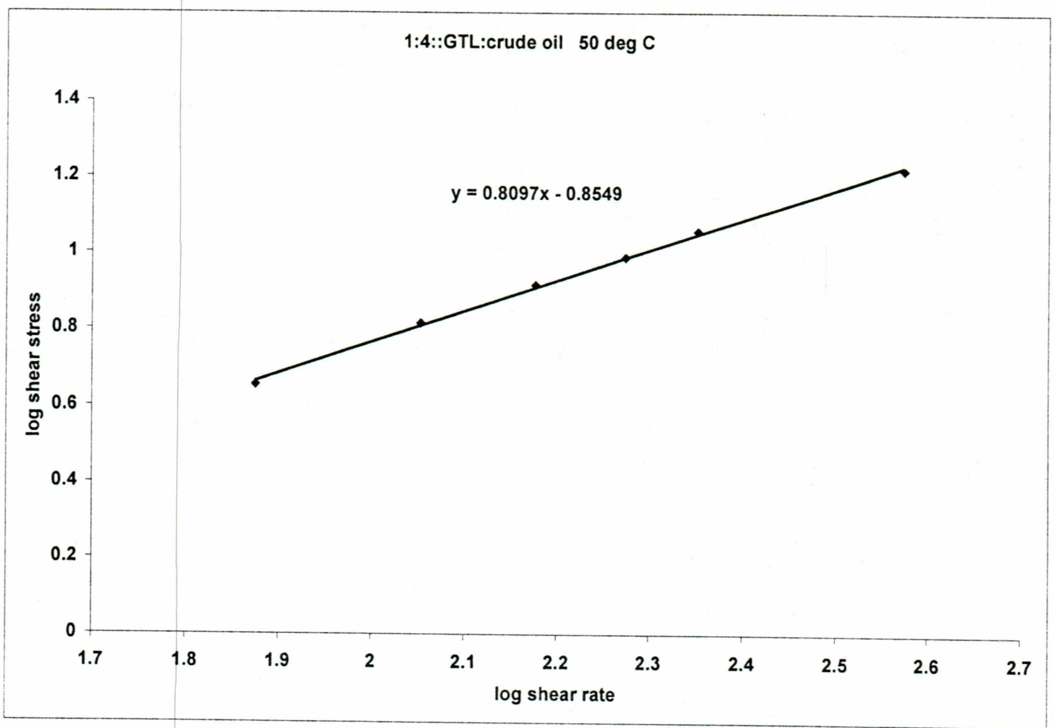

Figure 5.24b Log-log plot for BPGTL/Crude oil blend to find out n and k values (1:4 ratio at 50deg C)

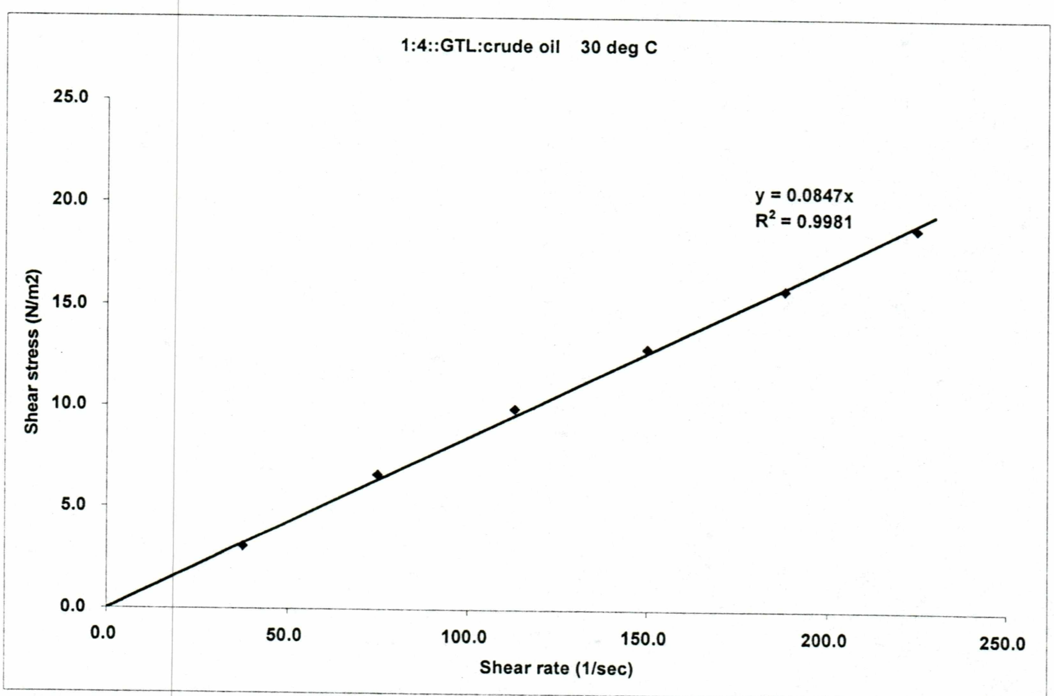

Figure 5.25 Rheogram for BPGTL/Crude Oil blend (1:4 ratio at 30 deg C)

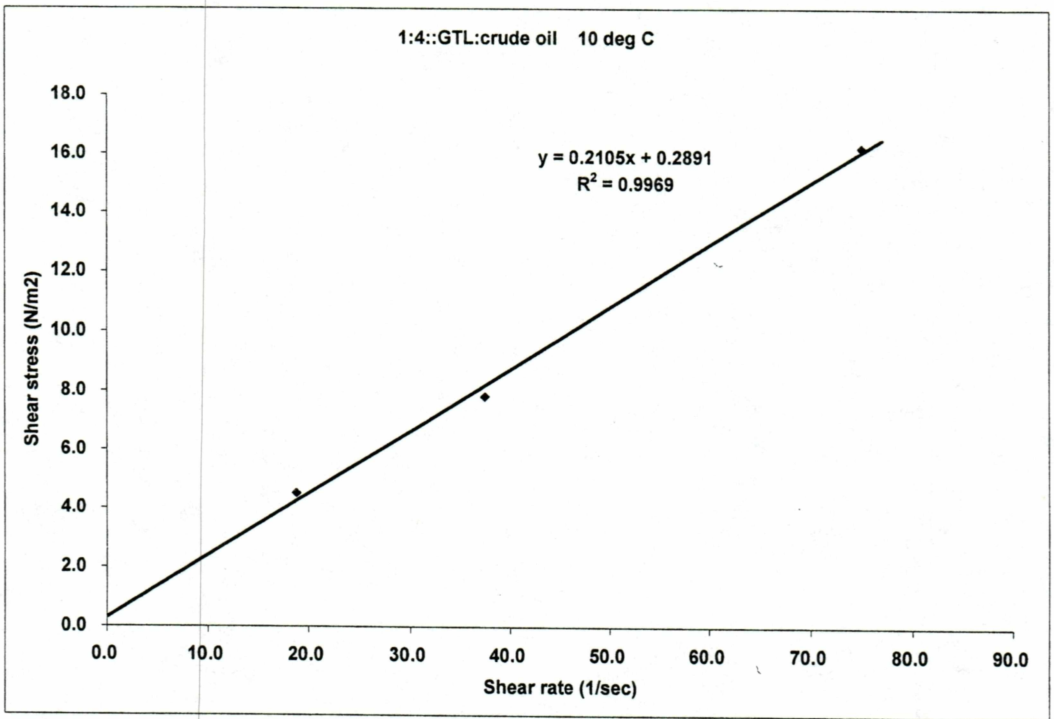

Figure 5.26 Rheogram for BPGTL/Crude Oil blend (1:4 ratio at 10 deg C)

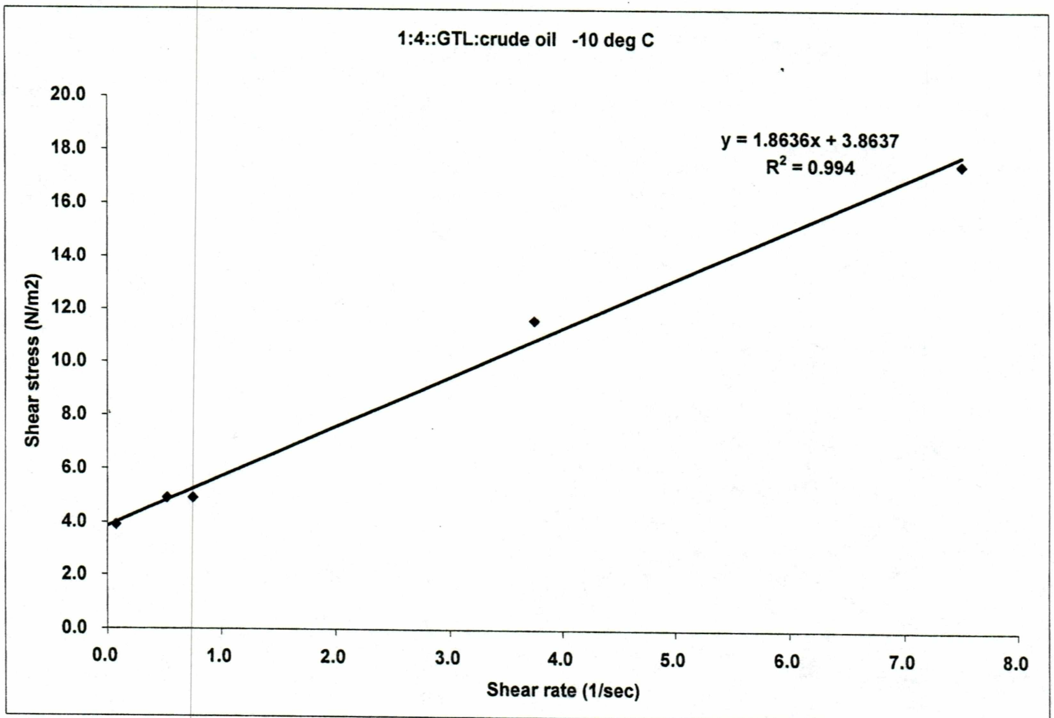

Figure 5.27 Rheogram for BPGTL/Crude Oil blend (1:4 ratio at -10 deg C)

5.2.4 GTL254, GTL302 and GTL344

The rheological evaluation of GTL cuts i.e. GTL254, GTL302 and GTL344 is summarized in table 5.11 below.

Table 5.11 Flow behavior parameters for GTL cuts

Fluid	Temp		Behavior	n		k ($lbf.s^n/100ft^2$)	
	deg C	deg F		rps < 375 1/sec	rps > 375 1/sec	rps < 375 1/sec	rps > 375 1/sec
GTL254	21	69.8	Pseudoplastic	0.3120	0.8600	1.1244	0.0417
	15	59	Pseudoplastic	0.2515	0.8550	1.5698	0.0447
	10	50	Pseudoplastic	0.3818	0.8995	0.7900	0.0383
	5	41	Pseudoplastic	0.4152	0.9350	1.1744	0.0288
GTL302	21	69.8	Pseudoplastic	0.4490	0.9640	0.7618	0.0329
	15	59	Pseudoplastic	0.2812	0.8008	1.6902	0.0793
	10	50	Pseudoplastic	0.2998	0.9023	1.6766	0.0460
	5	41	Pseudoplastic	0.3640	0.9483	1.2952	0.0372
GTL344	21	69.8	Pseudoplastic	0.5356	1.0114	0.3960	0.0230
	15	59	Pseudoplastic	0.3520	0.9931	1.2637	0.0275
	10	50	Pseudoplastic	0.3706	0.8600	1.1177	0.0624
	5	41	Pseudoplastic	0.4302	0.9789	1.4974	0.0403

5.3 APPLICATION OF PRESSURE DROP CALCULATION MODELS

The total pressure drop in TAPS while transporting fluid from pump station one to the Valdez Marine terminal is due to friction, elevation change and some other minor losses like fittings losses etc. Pressure losses due to acceleration are neglected since it is assumed that the flow rate is constant. For the calculation purpose TAPS is divided into 5 segments between pumpstation one (PS-1) on the slope and Valdez terminal (VDZ). Only the operating pumpstations are considered here. The center line elevation of each pump from sea level, elevation change between two consecutive pumpstations, distance of each pumpstation from PS1 is given in table 5.12. The table also shows the assumed values of minor losses which were used for calculations. These minor losses are considered constant for all the fluids. Total pressure drop along TAPS at various temperatures for GTL samples, Crude oil and their blends is tabulated below (See tables 5.13 and 5.14)

Table 5.12 Centre line elevation of each pump from sea level, elevation change between two consecutive pumpstations, distance of each pumpstation from PS1 and minor losses.

Stations	Elevation (ft)	Elev. Change between two consecutive pump stations (ft)	Distance between two consecutive pump stations (miles)	Total Distance from PS1 (miles)	Minor losses (Assumed) (psi)
PS-1	39			0	
PS-3	1383	1344	104.27	104.27	60.5
PS-4	2763	1380	39.79	144.06	52
PS-7	904	-1859	270.02	414.08	61
PS-9	1509	605	134.66	548.74	59
VDZ	166	-1343	251.46	800.32	62

5.3.1 Sample Calculations

Appropriate model is selected based on the rheological evaluation results (either Newtonian or Power law). The behavior of Crude oil, GTL and their blends is listed in tables 5.5 through 5.11. Pressure drop per mile is evaluated at various temperatures based on the daily throughput of 1.02 MMBPD.

1. Newtonian model

Example : Calculate the pressure drop per mile due to friction at various temperatures based on the daily throughput of 1.02 MMBPD of GTL/crude oil mixture in 1:1 ratio between pumpstations 1 and 3 (pipe segment 1).

Data:

Fluid = Crude oil and BPGTL blend (1:1 ratio)

Temperature = 20 deg C

Specific Gravity = 0.8215

Viscosity = 6.31 cp

Pipe I.D. = 46.98 inches

Pipe roughness = 0.00015 ft

Pipe length = 104.27 miles (1 mile = 5280 ft)

Elevation change = 1344 ft

Flow rate = 1.02 MMBPD

Solution: At 20 deg C the given fluid shows Newtonian behavior (see table 5.7). Hence we use the Newtonian model as discussed earlier to find out the pressure drop due to friction.

- Convert the flow rate from BPD to GPM using equation 4.21

$$q_{GPM} = \frac{1.02\times10^{6}\times42}{24\times60} = 29750 \text{ gpm}$$

- Calculate velocity of fluid using equation. 4.22

$$v = \frac{924\times29750}{720\times3.142\times46.98^{2}} = 5.505 \text{ ft/sec}$$

- Reynolds number is now calculated using equation. 4.23

$$N_{\text{Re}} = \frac{0.8215\times62.3709\times5.505\times46.98}{0.008064\times6.31} = 260{,}445$$

- Using equations. 4.25 and 4.26 we get A = 5.97E21 and B = 3.456E-14 respectively. Using these values of A and B and equation 4.24 we compute the friction factor as

$$f = 8\left[\left(\frac{8}{260445}\right)^{12} + (5.97E21 + 3.456E-14)^{-1.5}\right]^{1/12} = 0.01517$$

- Calculate head loss using equation 4.27;

$$H_f = \frac{0.01517\times5280\times5.505^{2}}{2\times46.98\times32.2} = 9.631 \text{ ft.}$$

- This head is converted to pressure using equation 4.28:

$$\left(\frac{dp}{dL}\right)_f = \frac{9.631}{2.31}\times0.8215 = 3.428 \text{ psi/ mile}$$

Similar steps are followed to calculate the frictional pressure drop per mile for all the fluids showing Newtonian behavior. These values are plotted in figure 5.89. To determine the total frictional pressure drop in between any two pumpstations simply multiply the pressure drop per mile values by the distance between the pumpstations.

- Total pressure drop is calculated using equation 4.36 as

$$\Delta P = 3.428\times104.27 + \frac{1344}{2.31}\times0.8215 + 60.5 = 895.9 \text{ psi}$$

Total pressure drop values are shown in table 5.13.

2. Power law model

Example : Calculate the pressure drop per mile due to friction at various temperatures based on the daily throughput of 1.02 MMBPD of GTL/crude oil mixture (1:1 ratio) between pumpstations 1 and 3 (pipe segment 1).

Data:

Fluid = Crude oil and BPGTL blend (1:1 ratio)

Temperature = 30 deg C

Specific Gravity = 0.8149

n = 0.925

k = 0.157 lbf-sec^n/100ft^2

Pipe I.D. = 46.98 inches

Pipe roughness = 0.00015 ft

Pipe length = 104.27 miles (1mile = 5280 ft)

Elevation change = 1344 ft

Flow rate = 1.02 MMBPD

Solution: At 30 deg C the given fluid shows Power law behavior (see table 5.7). Hence we use the Power law model as discussed earlier to find out the pressure drop due to friction.

- Convert the flow rate from BPD to GPM using equation 4.21

$$q_{GPM} = \frac{1.02\times 10^6 \times 42}{24\times 60} = 29750 \text{ gpm}$$

- Calculate velocity of fluid using equation. 4.22

$$v = \frac{924\times 29750}{720\times 3.142\times 46.98^2} = 5.505 \text{ ft/sec}$$

- Density = sp.gr. x 8.345 = 0.8149 x 8.345 = 6.8 lb/gal

- K = 510 x k = 510 x 0.157 = 80.1 eq.cp

- Reynolds number is now calculated using equation 4.29

$$N_{\mathrm{Re}} = \frac{89100\times 6.8\times 5.505^{(2-0.925)}}{80.1}\left(\frac{0.416\times 46.98}{3+1/0.925}\right)^{0.925} = 23{,}956$$

- Since $N_{Re} > 2100$, the flow is turbulent. Hence we use equation 4.31 to find out the frictional pressure drop. Friction factor f is obtained from figure 4.3

$$f = 0.0056$$

$$\left(\frac{dp}{dL}\right)_f = \frac{0.0056 \times 5280 \times 6.8 \times 5.505^2}{25.8 \times 46.98} = 5.029 \text{ psi/mile}$$

Similar steps are followed to calculate the frictional pressure drop per mile for all the fluids showing pseudoplastic behavior. These values are plotted in figures 5.90 through 5.92.

- Total pressure drop is calculated using equation 4.36 as

$$\Delta P = 5.029 \times 104.27 + \frac{1344}{2.31} \times 0.8149 + 60.5 = 1059 \text{ psi}$$

Total pressure drop values for pseudoplastic fluids are tabulated in table 5.14. It can be seen that pressure drop is more for pseudoplastic fluid than Newtonian fluid. Pressure drop for Bingham plastic fluids is not considered here since a) TAPS operating temperature usually is above 0 deg C and b) density below zero degrees Celsius was not measured because of the limitations of the densitometer. For someone interested in finding the pressure drop for Bingham plastic fluids the procedure is explained above.

In case of GTL pressure drop was calculated for rps >375 1/sec since the operating shear rates for TAPS are usually not less than 375 1/sec. The n values of rps>375 1/sec region are closer to one or one which is due to linearization of the shear stress shear rate curve. When the data points of shear rates less than 375 1/sec were neglected and best fit curve was drawn using excel through points (rps >375 1/sec) linear fit passing through origin was obtained. This shows Newtonian behavior. Thus pressure drop for GTL can be found using any of the above models for shear rps>375 1/sec region for analysis purpose. But for lower shear rates Power law model should be used. Also if values of n and k are averaged over the entire shear rate range Power law model should be used. Since in field GTL is going to show pseudoplastic behavior pressure drop is calculated using Power law model.

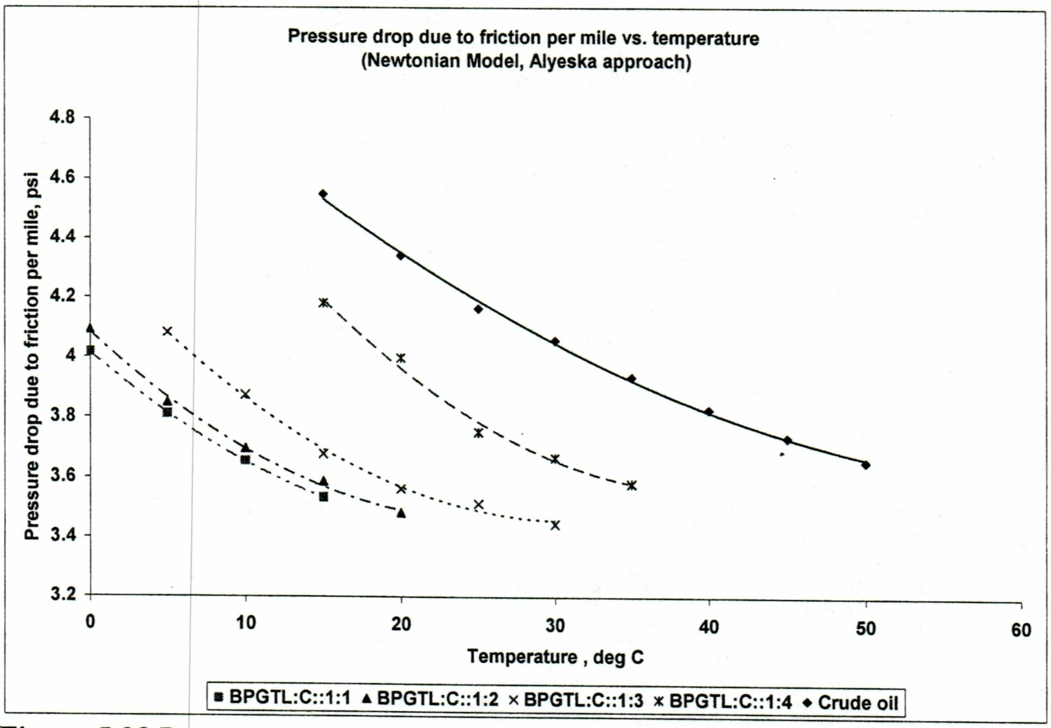

Figure 5.28 Pressure gradient due to friction while transporting Newtonian fluids.

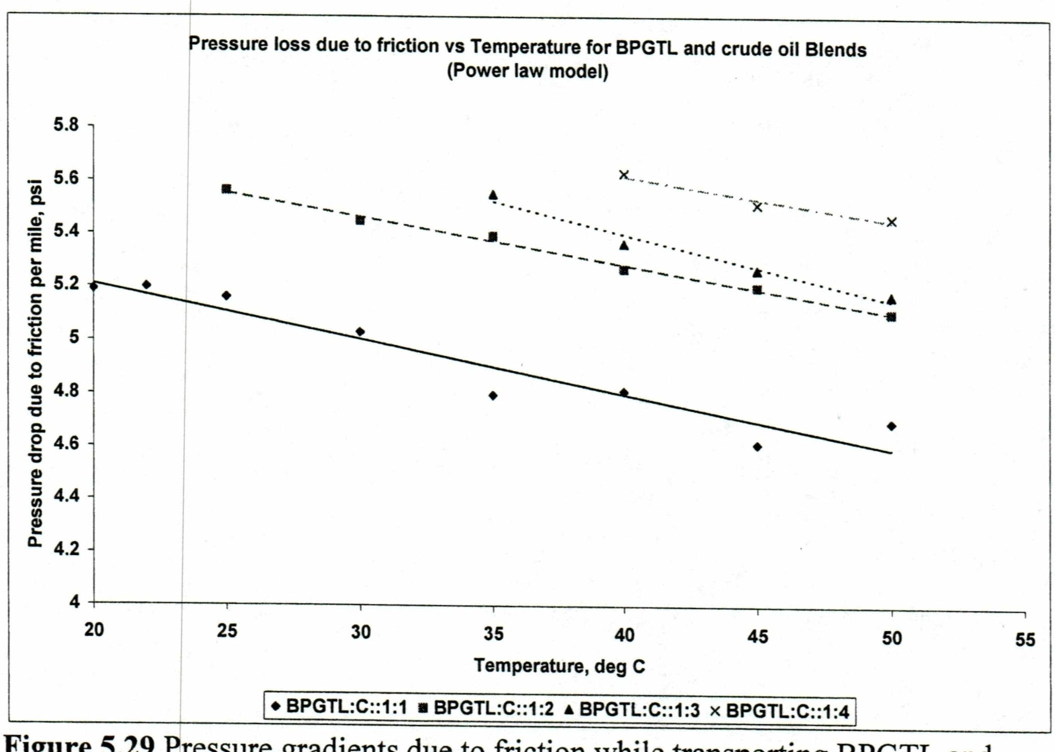

Figure 5.29 Pressure gradients due to friction while transporting BPGTL and crude oil blends

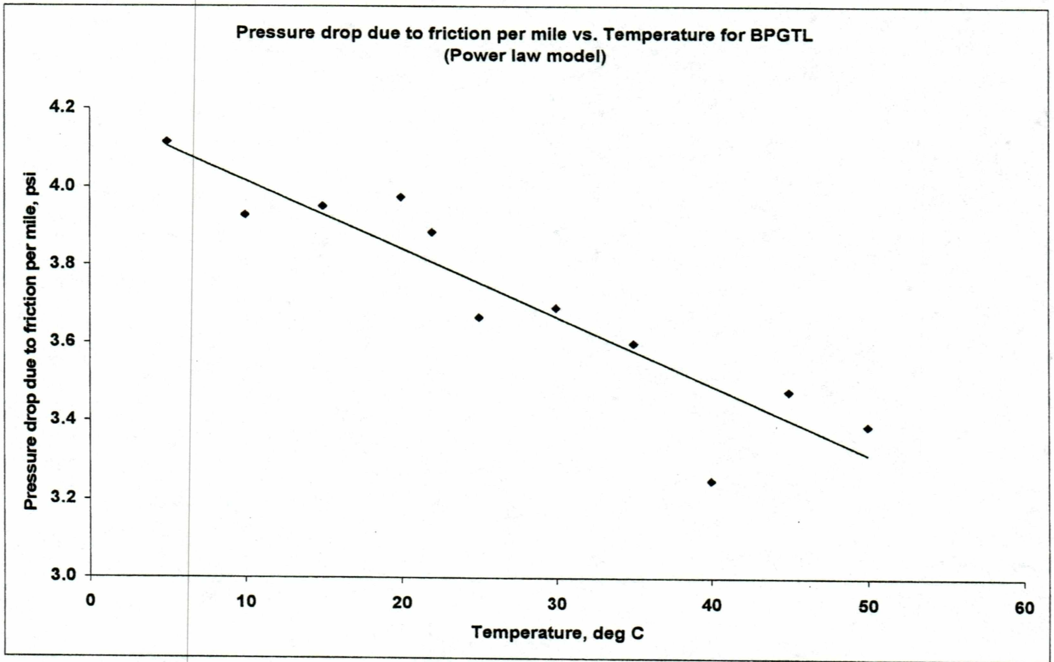

Figure 5.30 Pressure gradients due to friction while transporting BPGTL

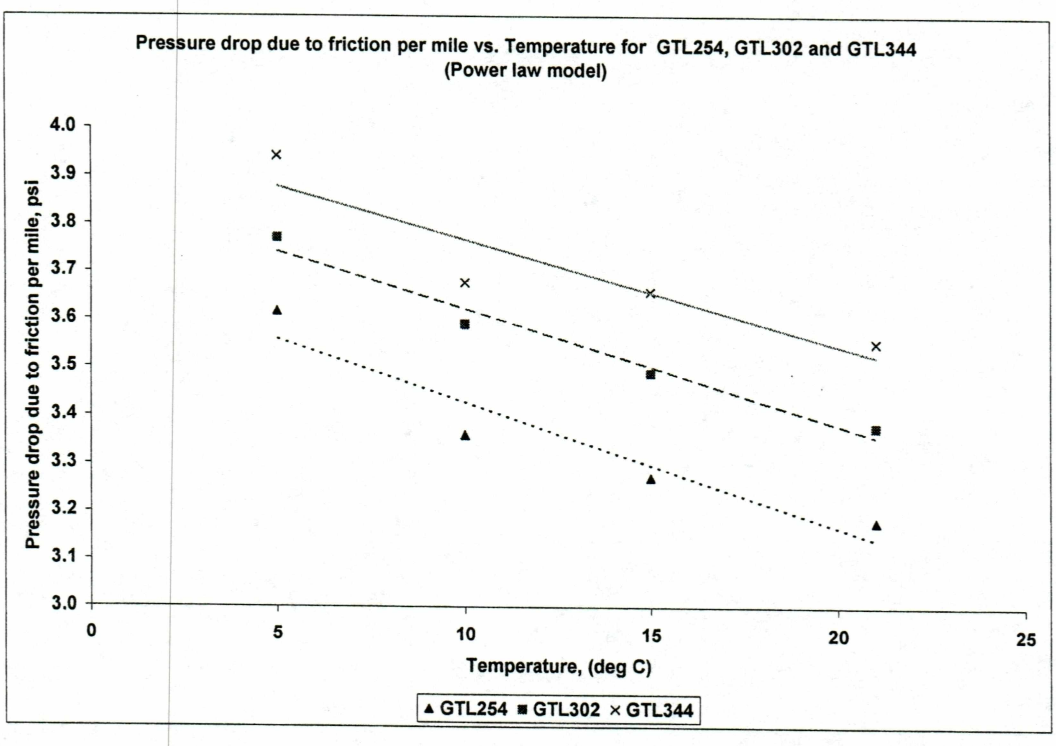

Figure 5.31 Pressure gradients due to friction while transporting GTL cuts.

Table 5.13 Total pressure drop for Newtonian fluids flowing through TAPS at various temperatures.

Fluid	Temperature		Total pressure drop				
	deg C	deg F	PS1 - PS3	PS3 - PS4	PS4 - PS7	PS7 - PS9	PS9 - VDZ
Crude oil	50	122	932.83	701.89	367.99	772.21	489.82
	45	113	941.73	705.66	388.73	783.21	509.30
	40	104	953.51	711.55	410.67	796.61	530.35
	35	95	967.85	718.97	435.79	812.58	554.62
	30	86	981.46	724.77	467.33	829.37	584.26
	25	77	993.06	729.50	495.54	843.97	610.66
	20	68	1013.56	738.63	540.52	868.72	653.14
	15	59	1037.20	749.00	593.43	897.50	703.02
1:1::GTL:crude oil	15	59	908.87	685.43	351.01	750.81	470.73
	10	50	923.55	692.34	380.93	768.05	499.18
	5	41	941.81	700.63	420.12	789.91	536.27
	0	32	965.31	710.87	473.12	818.60	586.19
1:2::GTL:crude oil	20	68	906.82	686.78	332.51	745.36	454.46
	15	59	919.80	693.09	357.81	760.36	478.62
	10	50	933.17	699.51	384.36	775.92	503.93
	5	41	951.40	707.89	422.77	797.60	540.34
	0	32	978.93	719.78	485.51	831.34	599.39
1:3::GTL:crude oil	30	86	901.11	683.37	325.38	739.61	447.26
	25	77	910.27	688.21	340.76	749.67	462.19
	20	68	917.36	692.20	351.27	757.17	472.55
	15	59	931.46	698.93	379.47	773.62	499.41
	10	50	953.92	708.85	429.31	800.86	546.43
	5	41	977.74	719.29	482.68	829.87	596.74
1:4::GTL:crude oil	35	95	919.91	693.62	355.09	759.87	476.31
	30	86	929.81	698.00	377.05	771.88	497.02
	25	77	940.55	703.38	397.00	784.09	516.18
	20	68	968.24	715.18	461.07	818.23	576.40
	15	59	989.37	724.56	507.71	843.81	620.42

Table 5.14a Total pressure drop for Power law fluids (Blends) flowing through TAPS at various temperatures.

Fluid	Temp deg C	Temp deg F	Total Pressure Drop PS1 - PS3	PS3 - PS4	PS4 - PS7	PS7 - PS9	PS9 - VDZ
1:1::GTL:crude oil	50	122	1017.97	719.18	682.07	901.98	775.51
	45	113	1009.67	716.31	658.74	890.87	753.91
	40	104	1032.62	726.46	709.61	918.70	801.91
	35	95	1033.72	728.68	701.36	917.77	795.03
	30	86	1059.04	738.94	763.25	949.69	852.93
	25	77	1074.49	746.12	795.40	967.98	883.44
	20	68	1079.40	749.19	600.25	972.75	888.93
1:2::GTL:crude oil	50	122	1065.69	740.65	785.54	959.35	873.32
	45	113	1076.27	745.07	810.64	972.53	896.87
	40	104	1085.46	749.93	826.12	982.64	911.89
	35	95	1101.06	757.72	855.18	1000.38	939.77
	30	86	1107.94	760.98	869.08	1008.44	953.00
	25	77	1121.64	767.45	896.93	1024.52	979.49
1:3::GTL:crude oil	50	122	1074.46	745.24	800.62	969.06	887.92
	45	113	1084.84	749.50	825.65	982.07	911.37
	40	104	1097.40	755.80	848.94	996.34	933.72
	35	95	1119.72	766.15	895.42	1022.77	977.83
1:4::GTL:crude oil	50	122	1110.74	762.88	871.24	1010.97	955.38
	45	113	1116.51	765.38	884.32	1018.03	967.70
	40	104	1130.78	772.21	912.73	1034.65	994.77

Table 5.14b Total pressure drop for Power law fluids (GTL) flowing through TAPS at various temperatures.

Fluid	Temp	Temp	Total Pressure D rop (rps>375 1/sec), psi				
	deg C	deg F	PS1 - PS3	PS3 - PS4	PS4 - PS7	PS7 - PS9	PS9 - VDZ
BP GTL	50	122	839.59	624.04	386.79	706.90	488.40
	45	113	849.40	628.27	409.19	718.93	509.48
	40	104	828.18	621.64	345.23	689.62	450.57
	35	95	867.50	638.52	435.50	737.96	535.47
	30	86	878.01	643.21	458.54	750.64	557.24
	25	77	877.45	644.27	449.24	748.26	549.15
	22	71.6	901.39	654.23	506.15	778.10	602.51
	20	68	911.70	658.73	529.39	790.68	624.41
	15	59	911.33	659.90	520.34	788.49	616.57
	10	50	911.15	661.22	511.31	786.44	608.78
	5	41	932.81	670.88	558.86	812.61	653.68
GTL254	21	69.8	811.62	609.35	339.10	676.02	442.19
	15	59	822.75	614.62	361.69	689.07	463.68
	10	50	833.09	619.27	384.07	701.50	484.85
	5	41	861.63	631.37	450.58	736.79	547.32
GTL302	21	69.8	837.14	622.24	385.77	704.86	487.06
	15	59	852.41	630.47	410.52	721.45	511.19
	10	50	865.33	636.94	434.49	736.13	534.20
	5	41	886.44	646.39	480.63	761.59	577.79
GTL344	21	69.8	856.84	630.78	430.55	728.99	529.22
	15	59	870.97	638.12	455.12	744.69	552.98
	10	50	875.04	641.06	457.10	748.13	555.44
	5	41	904.90	653.88	525.64	784.84	619.91

From tables 5.13 and 5.14 pressure drop along TAPS can be found out at various temperatures considering that particular temperature is constant throughout TAPS length. But as shown in table 2.3 temperatures along TAPS varies. An attempt is made to find out more practical pressure drop values in which an average of present TAPS temperature conditions between pump stations are considered as shown in table below. These average temperatures are assumed to remain constant throughout that particular pipe segment.

Table 5.15 Average temperatures between pumpstations.

Pipe segments	Temperature	
	deg C	deg F
PS1-PS3	35	95
PS3-PS4	30	86
PS4-PS7	20	68
PS7-PS9	15	59
PS9-VDZ	15	59

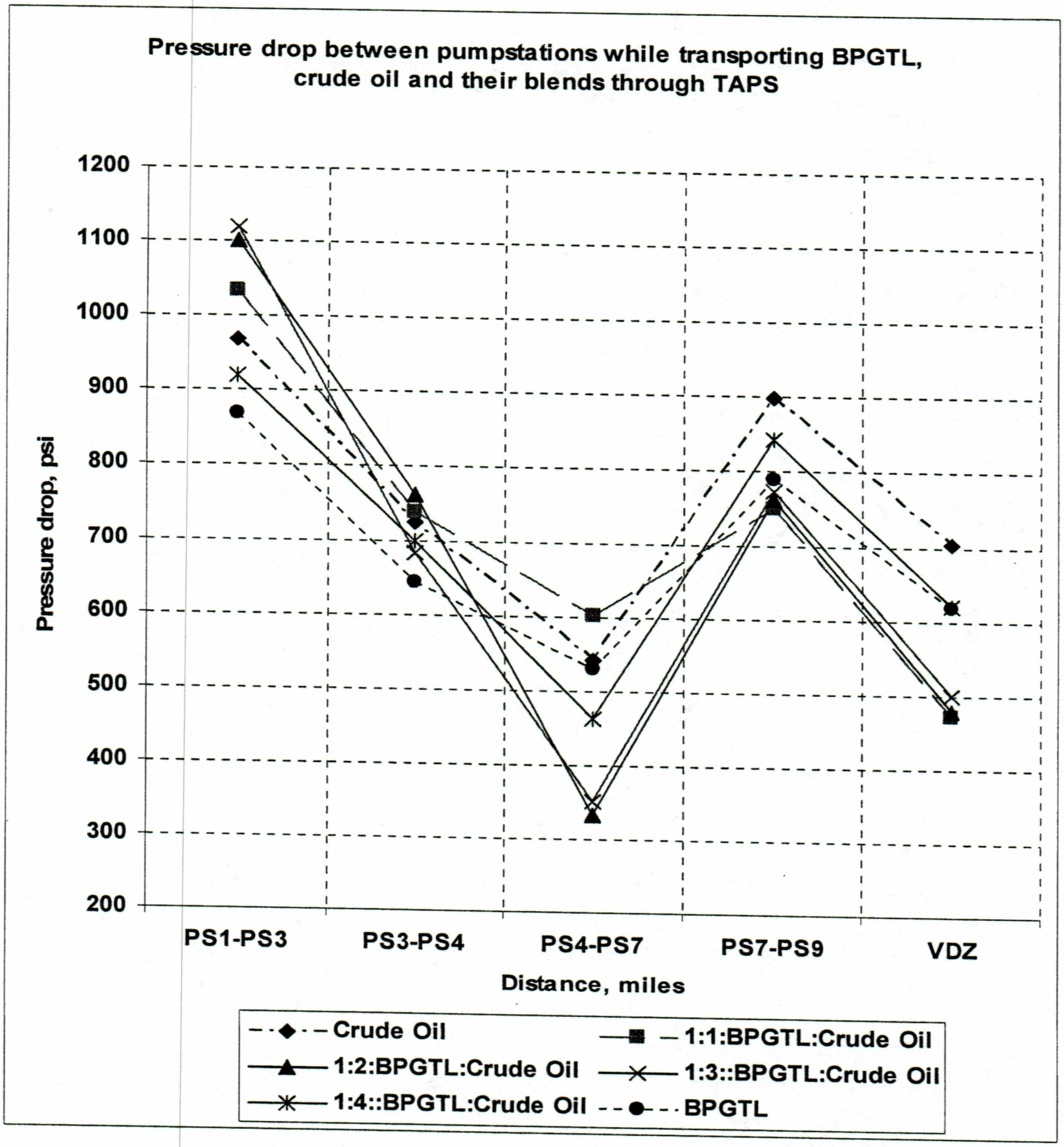

Figure 5.32 Total pressure drop between pumpstations along TAPS while transporting GTL, Crude oil and their blends at present temperature conditions.

5.4 POWER REQUIRED TO TRANSPORT THE FLUIDS BETWEEN PUMPSTATIONS

In this section hydraulic horsepower required to flow fluid between two consecutive pumpstations is calculated. From equation 4.41 it can be seen that hydraulic horsepower required to flow liquid from one pumpstation to another pumpstation depends on the flow rate and the pressure drop between two pumpstations. In this case flow rate is kept constant to 1.02 MMBPD. Pressure drop varies with temperature and fluid behavior. Thus hydraulic horsepower has varied in accordance with pressure drop variations in this work. Details about pump specifications, efficiency of pumps etc. are not considered here. The results are tabulated in tables 5.16 and 5.17 below. Hydraulic horsepower required between pumpstations at the present average temperature conditions (see table 5.15) for BPGTL, crude oil and their blends is shown in figure 5.33.

Table 5.16 Hydraulic horsepower required between pumpstations for transportation of Newtonian fluids through TAPS at various temperatures.

Fluid	Temp	Temp	Hydraulic horsepower (hp)				
	deg C	deg F	PS1 - PS3	PS3 - PS4	PS4 - PS7	PS7 - PS9	PS9 – VDZ
Crude oil	50	122	16191.25	12182.81	6387.29	13403.25	8501.83
	45	113	16345.70	12248.27	6747.15	13594.22	8839.87
	40	104	16550.07	12350.36	7127.95	13826.72	9205.29
	35	95	16799.01	12479.24	7563.98	14104.04	9626.52
	30	86	17035.21	12579.80	8111.45	14395.48	10141.03
	25	77	17236.68	12661.89	8601.09	14648.88	10599.34
	20	68	17592.37	12820.43	9381.79	15078.50	11336.59
	15	59	18002.78	13000.50	10300.16	15577.95	12202.34
1:1::GTL:crude oil	15	59	15775.33	11897.04	6092.57	13031.79	8170.48
	10	50	16030.05	12017.05	6611.79	13331.01	8664.22
	5	41	16346.99	12160.80	7292.11	13710.58	9307.99
	0	32	16754.86	12338.60	8211.93	14208.44	10174.51
1:2::GTL:crude oil	20	68	15739.65	11920.56	5771.48	12937.28	7888.09
	15	59	15964.98	12030.01	6210.58	13197.70	8307.51
	10	50	16197.12	12141.40	6671.30	13467.75	8746.77
	5	41	16513.43	12286.86	7337.98	13843.97	9378.71
	0	32	16991.29	12493.32	8427.02	14429.68	10403.69
1:3::GTL:crude oil	30	86	15640.70	11861.30	5647.64	12837.53	7763.14
	25	77	15799.55	11945.38	5914.57	13012.09	8022.22
	20	68	15922.69	12014.52	6097.04	13142.23	8202.07
	15	59	16167.44	12131.37	6586.41	13427.72	8668.30
	10	50	16557.29	12303.60	7451.56	13900.62	9484.48
	5	41	16970.77	12484.84	8377.87	14404.02	10357.63
1:4::GTL:crude oil	35	95	15966.87	12039.20	6163.30	13189.09	8267.28
	30	86	16138.82	12115.24	6544.41	13397.57	8626.85
	25	77	16325.24	12208.53	6890.75	13609.43	8959.31
	20	68	16805.81	12413.42	8002.86	14202.03	10004.60
	15	59	17172.61	12576.20	8812.32	14646.00	10768.63

Table5.17a Hydraulic horsepower required between pumpstations for transportation of Power law fluids (Blends) TAPS at various temperatures.

Fluid	Temp	Temp	Hydraulic horsepower (hp)				
	deg C	deg F	PS1 - PS3	PS3 - PS4	PS4 - PS7	PS7 - PS9	PS9 - VDZ
1:1::GTL:crude oil	50	122	17668.93	12482.83	11838.80	15655.71	13460.49
	45	113	17524.94	12433.09	11433.82	15462.95	13085.68
	40	104	17923.21	12609.18	12316.76	15945.87	13918.72
	35	95	17942.28	12647.73	12173.55	15929.70	13799.35
	30	86	18381.86	12825.90	13247.72	16483.82	14804.36
	25	77	18650.04	12950.39	13805.79	16801.27	15333.99
	20	68	18735.25	13003.76	10418.57	16884.13	15429.26
1:2::GTL:crude oil	50	122	18497.18	12855.57	13634.60	16651.43	15158.23
	45	113	18680.95	12932.22	14070.38	16880.27	15566.97
	40	104	18840.46	13016.54	14339.03	17055.68	15827.65
	35	95	19111.12	13151.75	14843.34	17363.60	16311.60
	30	86	19230.63	13208.44	15084.63	17503.50	16541.26
	25	77	19468.45	13320.69	15568.08	17782.59	17001.11
1:3::GTL:crude oil	50	122	18649.40	12935.16	13896.41	16819.99	15411.67
	45	113	18829.58	13009.13	14330.90	17045.88	15818.63
	40	104	19047.62	13118.40	14735.07	17293.49	16206.69
	35	95	19435.05	13298.17	15541.77	17752.20	16972.23
1:4::GTL:crude oil	50	122	19279.18	13241.30	15122.08	17547.50	16582.55
	45	113	19379.30	13284.72	15349.26	17670.01	16796.45
	40	104	19626.99	13403.34	15842.24	17958.45	17266.34

Table5.17b Hydraulic horsepower required between pumpstations for transportation of Power law fluids (GTL) TAPS at various temperatures.

Fluid	Temp	Temp	Hydraulic horsepower (hp)				
	deg C	deg F	PS1 - PS3	PS3 - PS4	PS4 - PS7	PS7 - PS9	PS9 – VDZ
BP GTL	50	122	14572.76	10831.54	6713.53	12269.70	8477.18
	45	113	14743.02	10904.99	7102.29	12478.54	8843.02
	40	104	14374.78	10789.88	5992.23	11969.85	7820.63
	35	95	15057.25	11082.89	7558.97	12808.75	9294.27
	30	86	15239.61	11164.21	7958.99	13028.96	9672.04
	25	77	15229.93	11182.67	7797.52	12987.58	9531.59
	22	71.6	15645.42	11355.55	8785.22	13505.47	10457.81
	20	68	15824.43	11433.63	9188.60	13723.90	10837.84
	15	59	15818.04	11454.00	9031.62	13685.91	10701.87
	10	50	15814.84	11476.89	8874.90	13650.35	10566.71
	5	41	16190.83	11644.48	9700.14	14104.49	11346.02
GTL254	21	69.8	14087.36	10576.60	5885.81	11733.74	7675.15
	15	59	14280.56	10667.92	6277.80	11960.30	8048.07
	10	50	14460.05	10748.79	6666.40	12175.97	8415.50
	5	41	14955.40	10958.67	7820.78	12788.51	9499.87
GTL302	21	69.8	14530.26	10800.34	6695.76	12234.36	8453.92
	15	59	14795.31	10943.19	7125.37	12522.29	8872.68
	10	50	15019.50	11055.45	7541.45	12776.99	9272.12
	5	41	15386.06	11219.44	8342.26	13218.95	10028.68
GTL344	21	69.8	14872.28	10948.45	7473.13	12653.12	9185.74
	15	59	15117.53	11075.92	7899.62	12925.68	9598.09
	10	50	15188.11	11126.96	7933.94	12985.39	9640.84
	5	41	15706.39	11349.50	9123.64	13622.44	10759.85

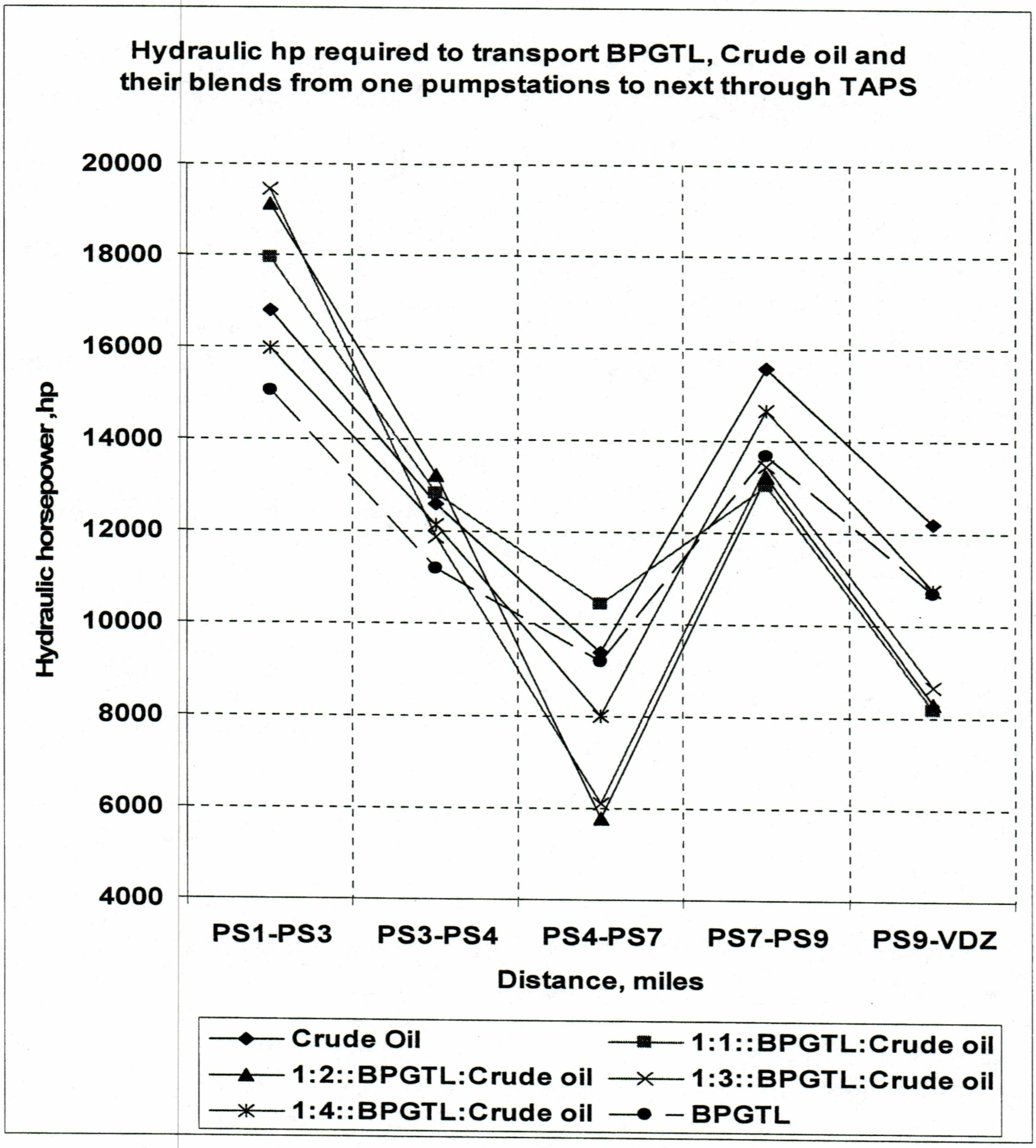

Figure 5.33 Hydraulic horsepower required between pumpstations for transporting GTL, crude oil and their blends through TAPS at present temperature conditions.

5.5 OPTIMUM BLEND RATIO OR OPTIMUM AMOUNT OF GTL IN THE GTL/ANS CRUDE OIL BLEND

In this work four blend ratios 1:1 (50 %GTL), 1:2 (33.33% GTL), 1:3 (25%GTL) and 1:4 (20% GTL) were considered. Also pure GTL (100% GTL) and pure crude oil (0% GTL) properties were studied. Rheological properties were evaluated for all these fluids at various temperatures. Pressure drop due to elevation, friction and other minor losses was calculated at TAPS temperature condition by taking an average of temperatures between the pumpstations. Finally the hydraulic horsepower required (HHP) to flow GTL, crude oil and their blends through TAPS was determined. This hydraulic horsepower is a function of pressure drop and fluid flow rate. Since flow rate through the TAPS was kept constant hydraulic horsepower is proportional to the total pressure drop. Thus to determine optimum blend ratio or optimum amount of GTL in the blend, average pressure drop per mile due to respective fluid is calculated and plotted against percentage amount of GTL in blend (see figure 5.34). The minimum of this curve gives the optimum amount of GTL in the GTL/crude oil blend. But it should be noted that various factors such as flow behavior parameters of the fluid, pipeline characteristics, elevation changes, temperature conditions among others are responsible for this pressure drop. Hence optimum blend ratio also depends on all these parameters.

From figure 5.34 it can be seen that at 28% of GTL, the curve shows minimum. Thus 28% GTL in GTL/ANS Crude oil blend is the optimum blend ratio.

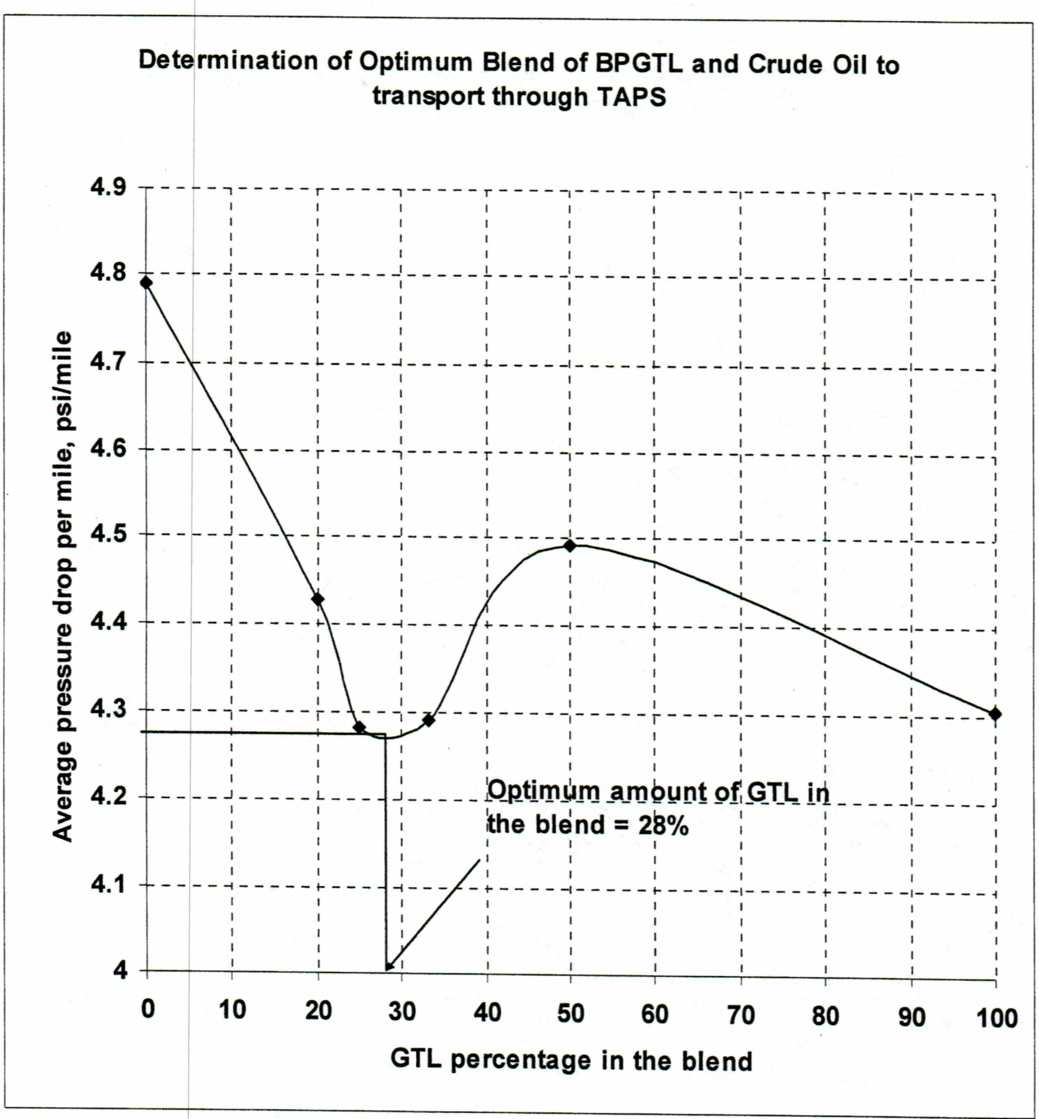

Figure 5.34 Optimum amount of GTL in the GTL/ANS Crude Oil blend.

CHAPTER 6

CONCLUSIONS AND RECOMMENDATION

6.1 CONCLUSIONS

Based on the shear stress vs. shear rate relationship, flow behavior parameters n & k and viscosity of the fluids first three conclusions are made. Rest of the conclusions are drawn from overall work.

i. BPGTL shows pseudoplastic behavior at all temperatures in the given temperature range (50 deg C to -20 deg C).

ii. Crude Oil shows Newtonian behavior at temperatures 20 deg C and above and shows Bingham plastic behavior below 20 deg C.

iii. Blends of BPGTL and Crude Oil shows Pseudoplastic behavior at higher temperatures (above room temperature), Newtonian at intermediate temperatures (around room temperature) and Bingham plastic behavior at lower temperatures (near zero degree Celsius and below) in the given temperature range.

iv. Viscosity and density of blends decrease with increasing amount of GTL as well as increasing temperature.

v. Hydraulic horse power required to transport pseudoplastic fluids is more than that of Newtonian fluids due to the higher pressure drop obtained from pseudoplastic fluids.

vi. The blend containing 28% GTL and 72% crude oil ratio is the optimum blend which is function of various parameters such as fluid temperature, flow behavior parameters, pipeline characteristics, elevation changes in pipeline among others.

6.2 RECOMMENDATION

The recommendation for future work is: using the optimum blend ratio (28% GTL) and its characteristic parameter(s),an economic evaluation should be studied and compared to other blend ratios.

NOMENCLATURE

d	- Inside diameter of pipe, in.
f_m	- Moody or Darcy friction factor
f'	- Fanning friction factor
h	- specific enthalpy
H	- head, ft
H_f	- head due to friction, ft
H_{el}	- head due to elevation or elevation change, ft
k	- consistency index factor
K	- Consistency index of power law model, eq. cp.
L	- Length of pipe, ft
M	- total mass of the blend that will give the required volume
n	- Flow behavior index of power law model
N_{Re}	- Reynolds number
p	- pressure
q_{BPD}	- flow rate in barrels per day
q_{GPM}	- flow rate in gallons per minute
q_{SBPH}	- flow rate in standard barrels per hour
q`	- heat energy added to fluid
Q	- fluid flow rate, gpm
R^2	- regression coefficient
S	- entropy
T	- temperature, ^{o}C
TE_{coeff}	- thermal expansion coefficient
U'	- internal energy
v	- velocity of fluid, ft/sec
W_s`	- work done on the fluid

z - elevation above reference datum, ft

μ - viscosity of fluid, cp

μ_p - Plastic viscosity of Bingham model, cp

τ_y - yield point of Bingham plastic model, lb/100 ft^2

τ - shear stress, lb/100 ft^2

$\in_{xy}$ - strain rate

$\dot{\gamma}$ - shear rate, 1/sec

α - the mass fraction of GTL in the blend

ρ_G - density of GTL, gm/cc

ρ_C - density of Crude Oil, gm/cc

ΔP - total pressure drop, psi

ΔP_{el} - pressure drop due to elevation, psi

$\Delta P_{\min or}$ - pressure drop due to minor losses, psi

ε - roughness of pipe, ft

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